Prospect for a ridge in p+Pb collisions

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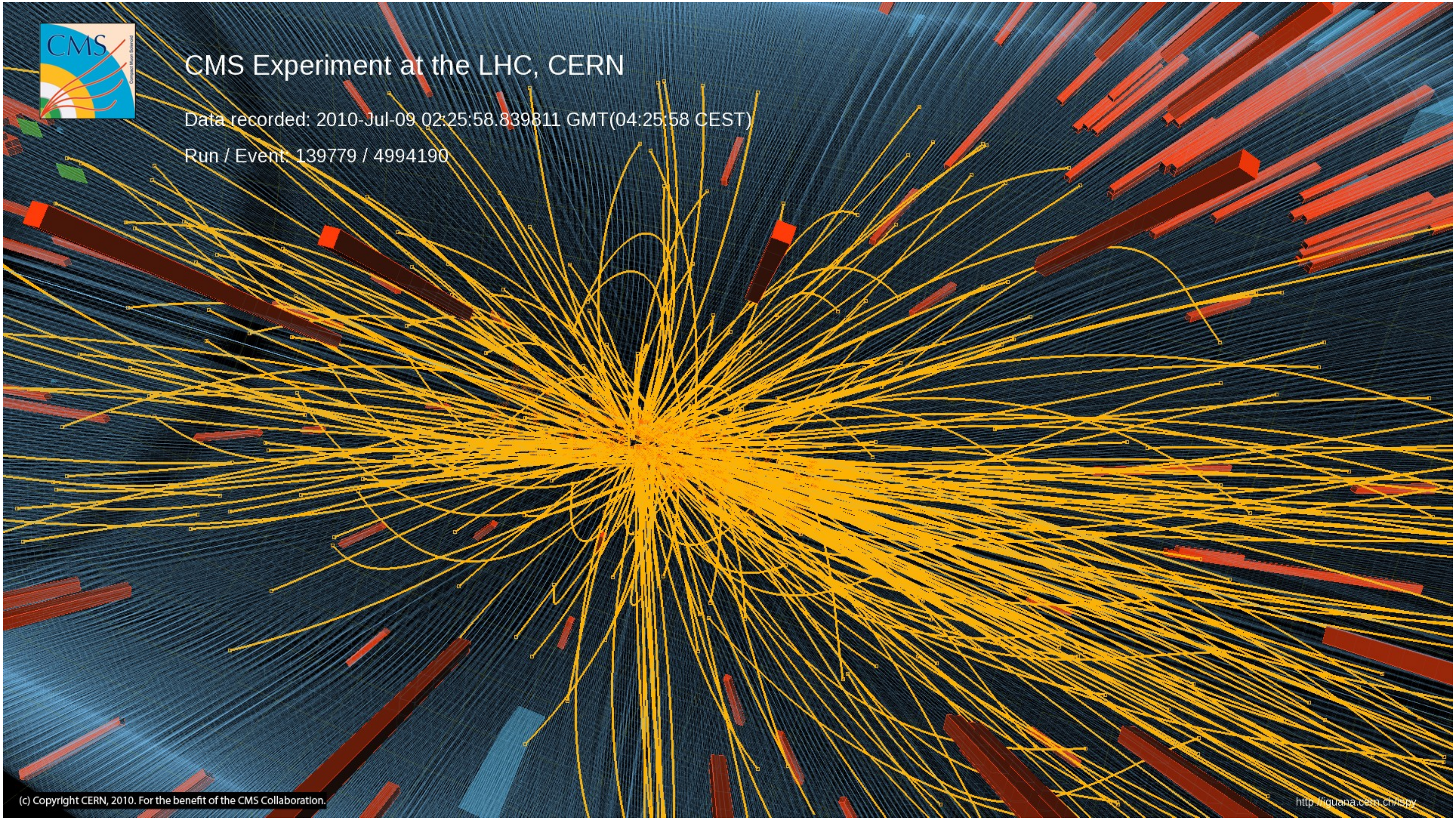
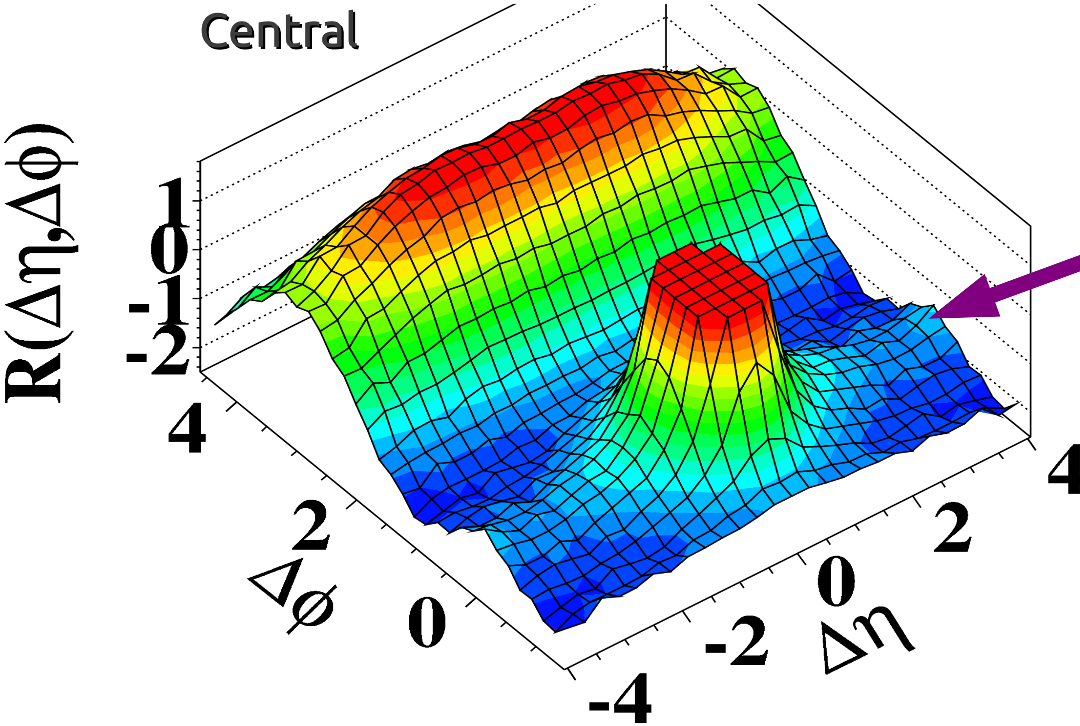
NC STATE UNIVERSITY

The Ridge



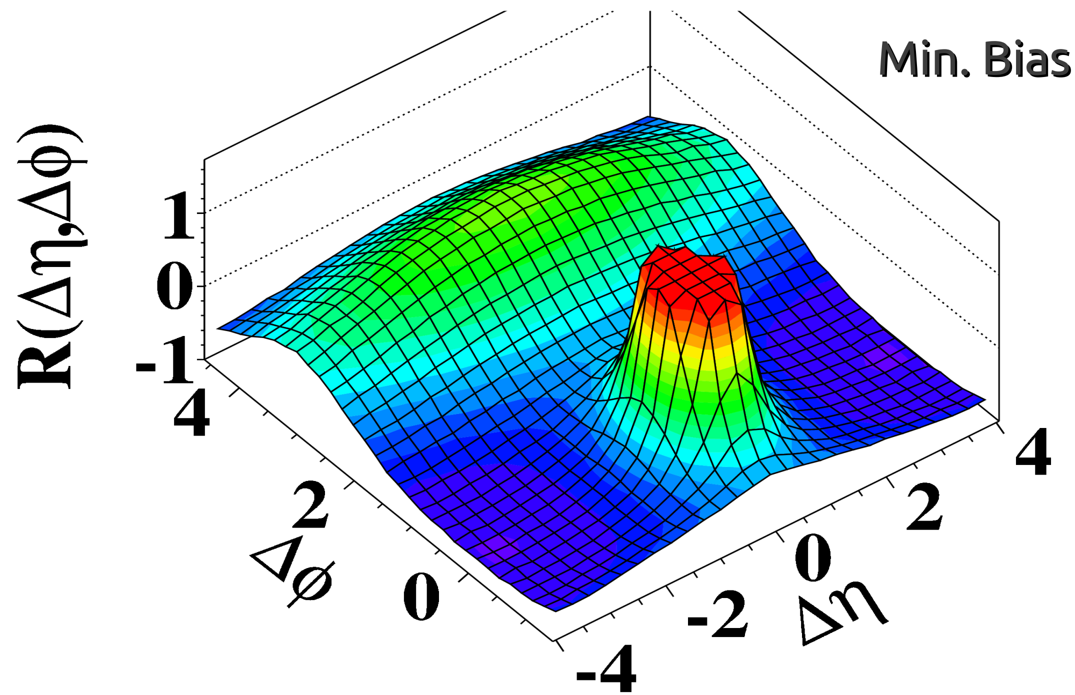
More than 200 charged particles!



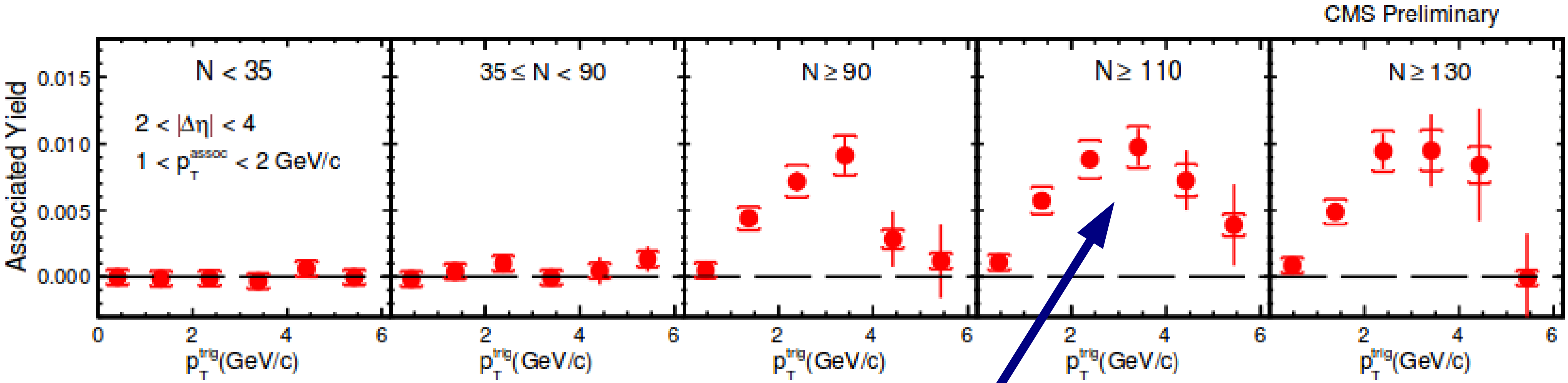
The Ridge

CMS N $\geq$ 110

$1.0 < p_T[\mathrm{GeV}] < 3.0$

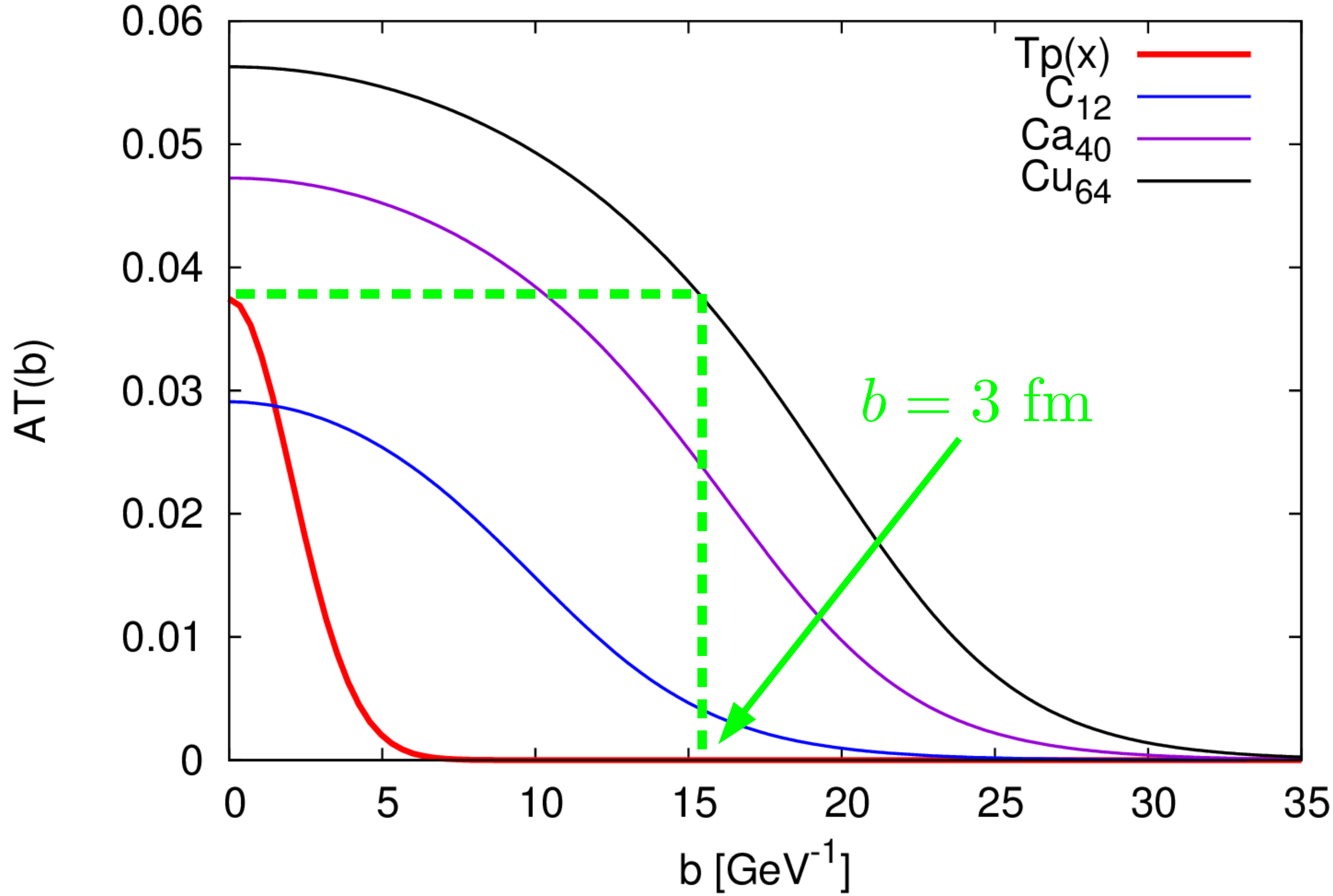


The Ridge



1. There is a clear scale in the data
2. It is semi-hard and will be argued to be Q_s

Multiplicity the same as in Cu+Cu !



Wave function of the proton

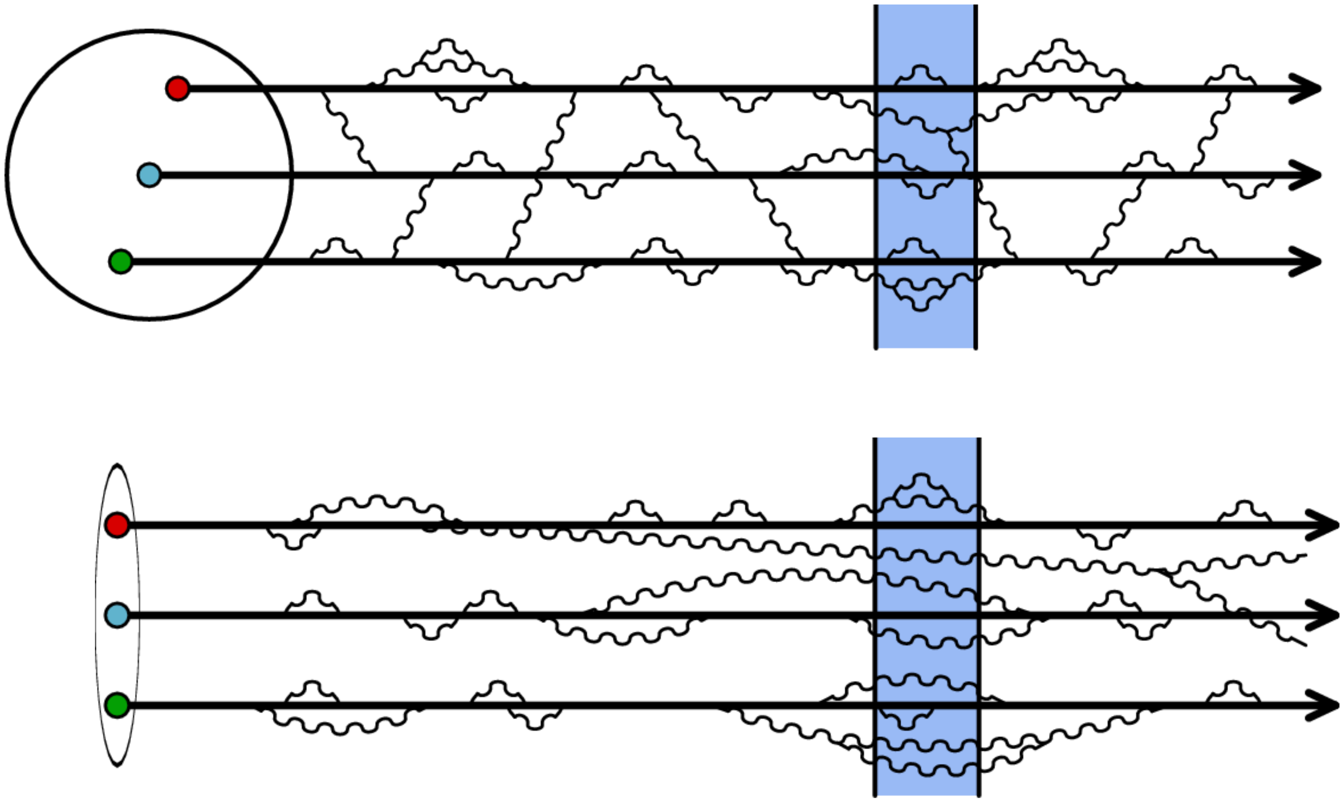
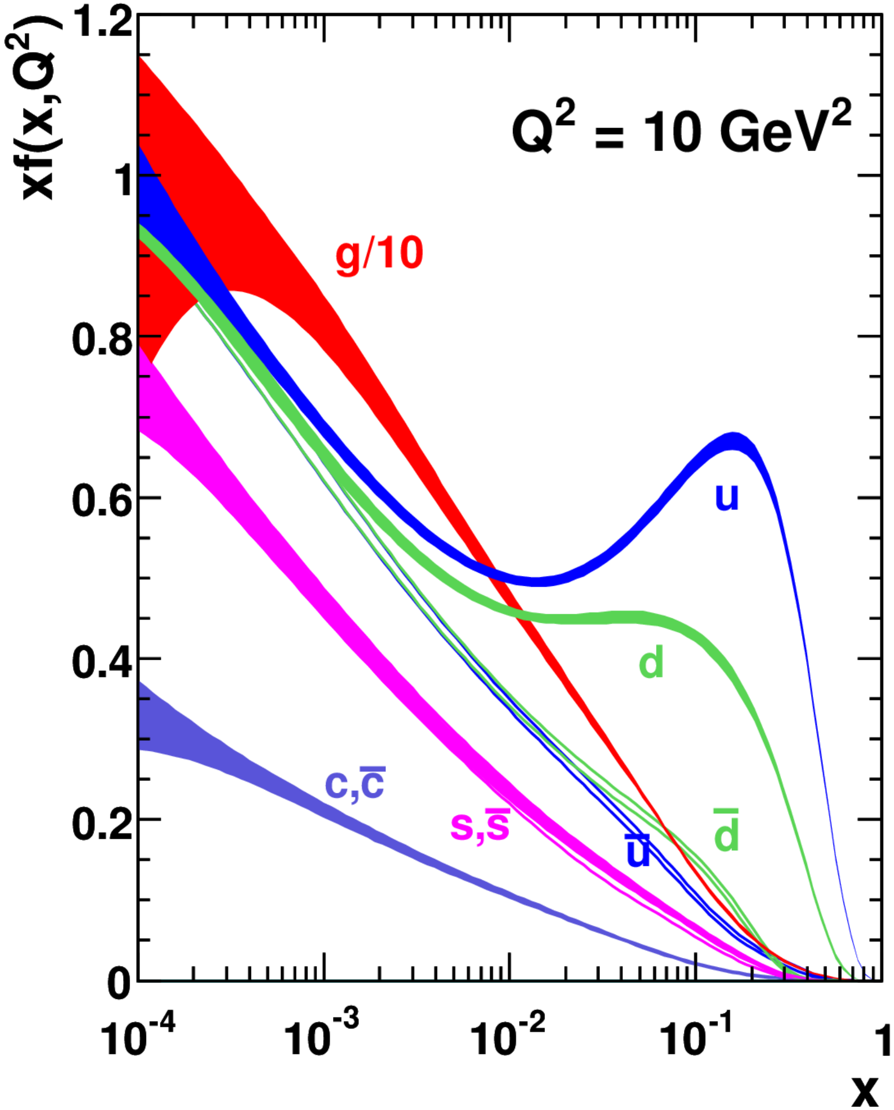


Figure courtesy of Francois Gelis

$$x \sim 10^{-2} \text{ at } \sqrt{s} = 200 \text{ GeV}$$

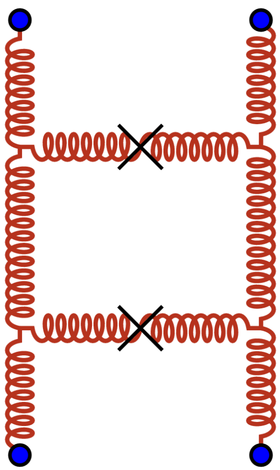
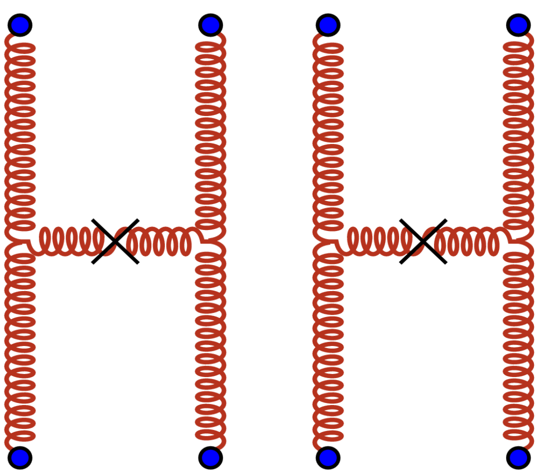
$$x \sim 10^{-4} \text{ at } \sqrt{s} = 7 \text{ TeV}$$



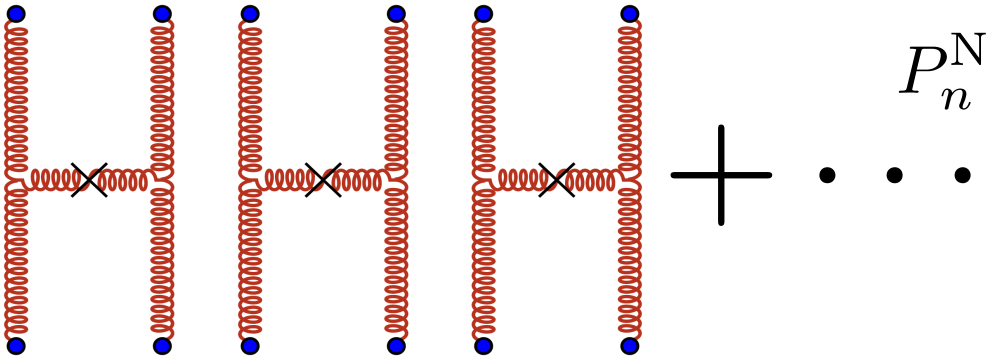
Growth of gluon distribution function at small x is seen experimentally.

Data / figures from: http://mstwpdf.hepforge.org/

The role of STRONG color sources

Diagram:	Min. Bias	Central
	$\mathcal{O}\left(\alpha_s^4\right)$	$\mathcal{O}\left(1\right)$
	$\mathcal{O}\left(\alpha_s^6\right)$	$\mathcal{O}\left(\alpha_s^{-2}\right)$

High multiplicity are b=0 collisions



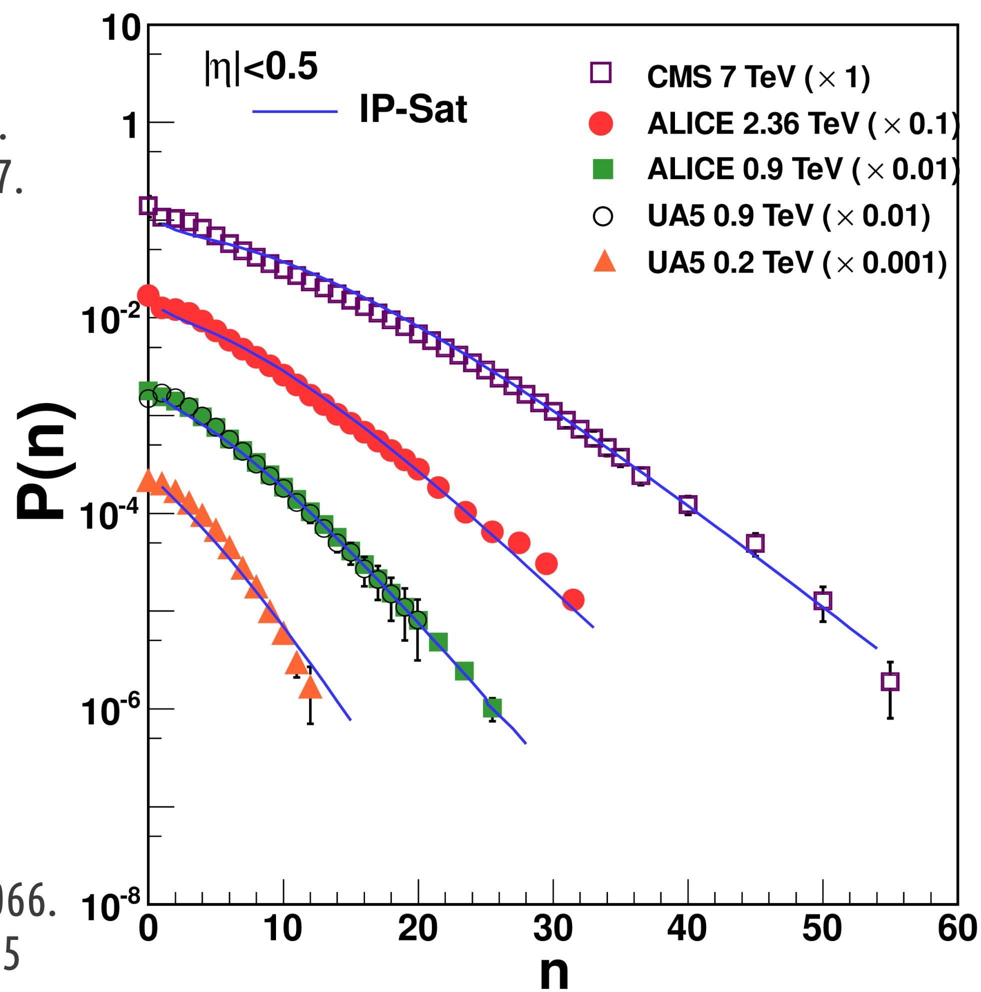
$$P_n^{\mathrm{NB}}(\overline{n}, k) = \frac{\Gamma(k+n)}{\Gamma(k)\Gamma(n+1)} \frac{\overline{n}^n k^k}{(\overline{n}+k)^{n+k}}$$

Dumitru, Gelis, McLerran, Venugopalan, NPA810 91-108 (2008).
Dusling, Fernandez-Fraile, Venugopalan NPA828 (2009) 161-177.
Gelis, Lappi, McLerran, NPA828 (2009) 149-160.

$$k = \zeta \frac{\left(N_c^2 - 1\right) S_\perp Q_s^2}{2\pi}$$

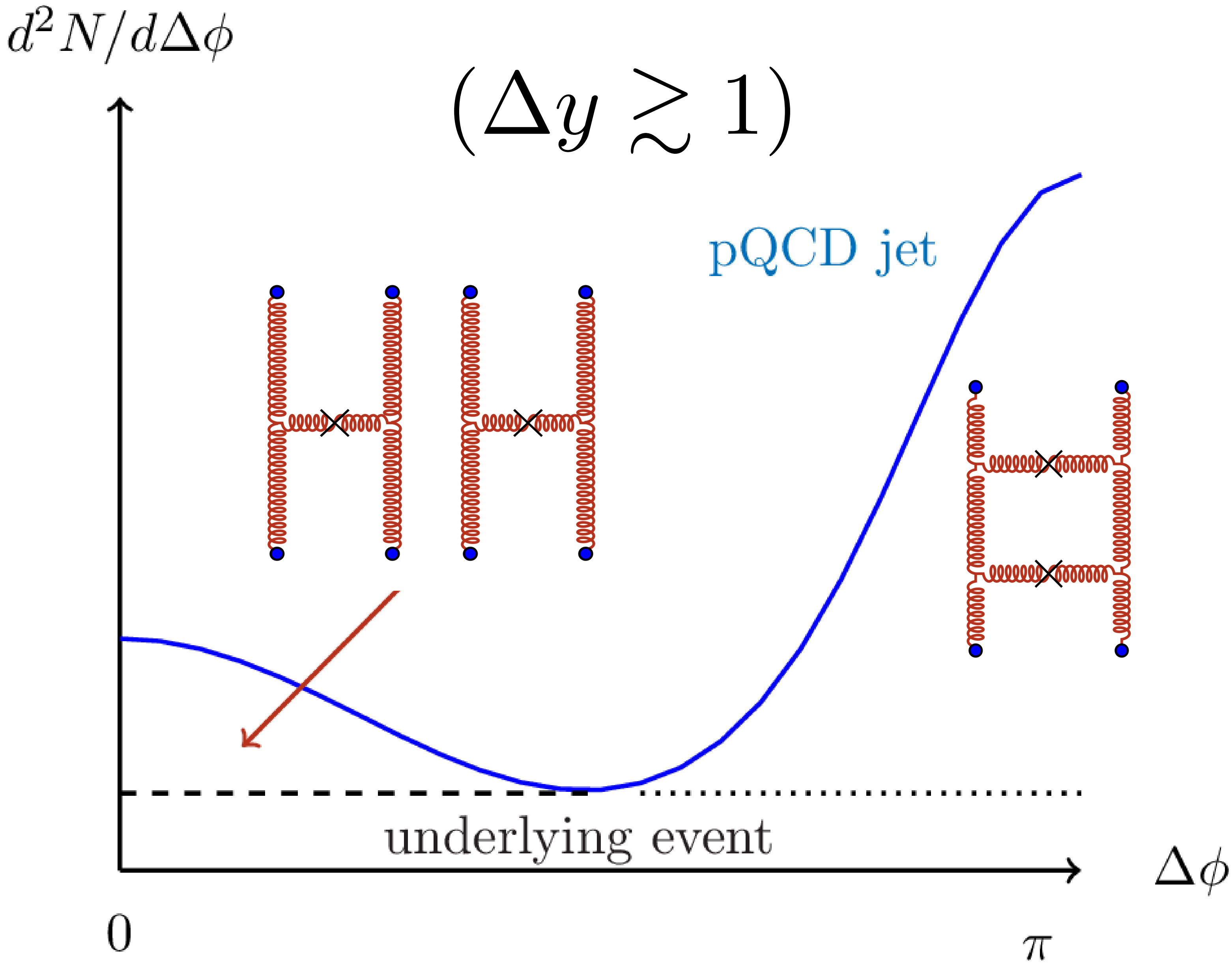
$$\zeta = 0.155 \ \ [\mathrm{Empirical}]$$

$$\zeta = 0.2 - 1.5 \ \ [\mathrm{Lattice}]$$



Emprical: Tribedy, Venugopalan, NPA850 (2011) 136-156.
Lattice (CYM): Lappi, Srednyak, Venugopalan, JHEP01 (2010) 066.
Schenke, Tribedy, Venugopalan, arXiv:1206.6805

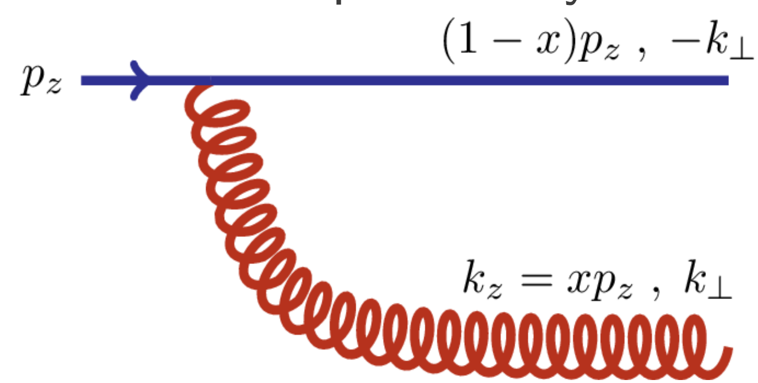
Forward jet structure



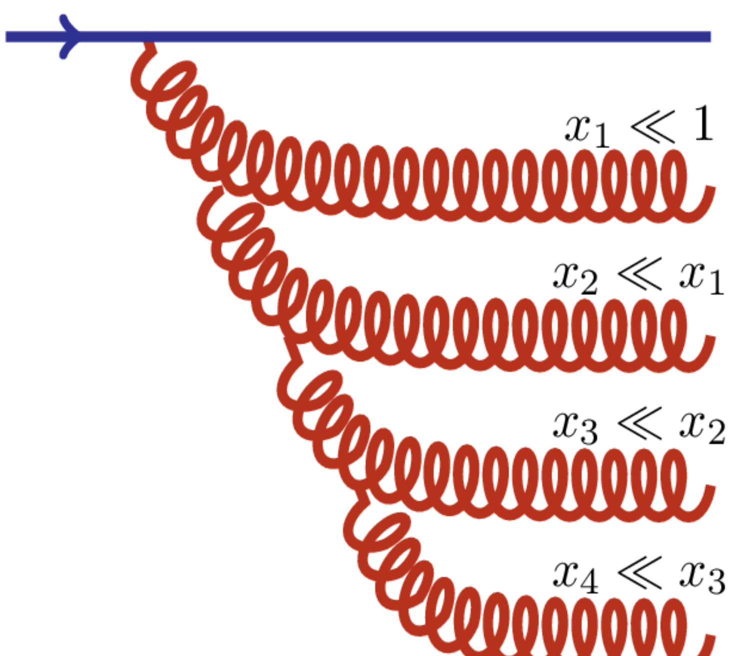
Gluon radiation

As the energy is increased new gluons are emitted with probability

$$\mathrm{d}P_{\mathrm{Brem}} \sim C_R \frac{\alpha_s}{\pi^2} \frac{\mathrm{d}^2 k_\perp}{k_\perp^2} \frac{\mathrm{d}x}{x}$$



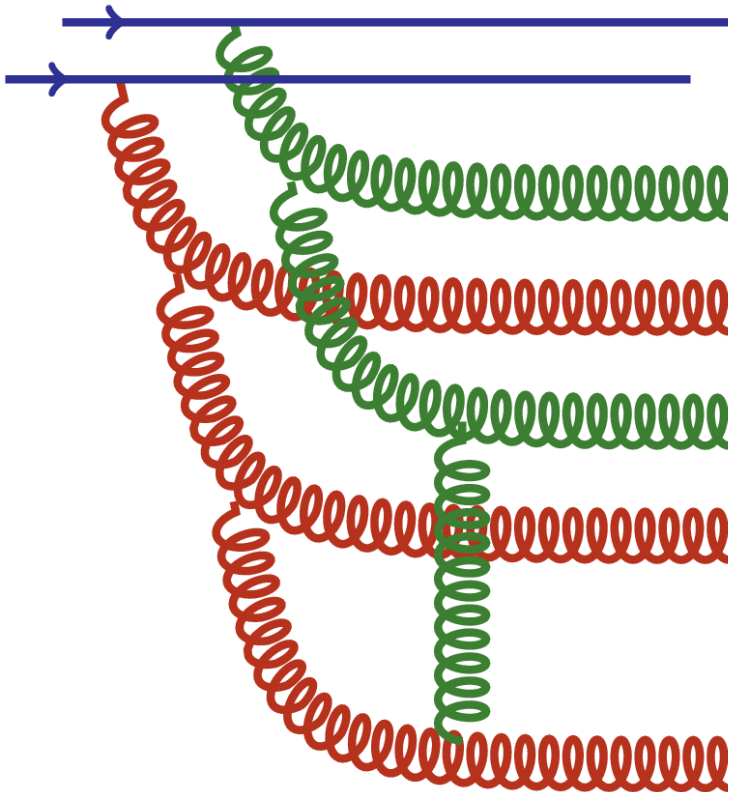
And as long as the density remains low the evolution is linear



$$\frac{\partial T(\mathbf{r}_\perp, Y)}{\partial Y} = \frac{\alpha_s N_c}{2\pi^2} \int \mathrm{d}\mathbf{r}_1 \, \frac{\mathbf{r}_\perp^2}{\mathbf{r}_1^2 \left(\mathbf{r}_\perp - \mathbf{r}_1\right)^2} \times$$
$$[T(\mathbf{r}_1, Y) + T(\mathbf{r}_\perp - \mathbf{r}_1, Y) - T(\mathbf{r}_\perp, Y)]$$

Kuraev, Lipatov, Fadin, Sov.Phys.JETP44 443-450 (1976).
Sov.Phys.JETP45 199-204 (1977).
Balitsky, Lipatov, Sov.J.Nucl.Phys 28 822-829 (1978).

BK Evolution Equation



Balitsky, NPB 463, 99 (1996).
Kovchegov, PRD 60, 034008 (1999).

Jalilian-Marian, Kovner, McLerran, Weigert, PRD 55 5414 (1997).
Jalilian-Marian, Kovner, Leonidov, Weigert, NPB 504 415 (1997),
PRD 59 014014 (1999).

$$\frac{\partial T(\mathbf{r}_\perp, Y)}{\partial Y} = \frac{\alpha_s N_c}{2\pi^2} \int \mathrm{d}\mathbf{r}_1 \, \frac{\mathbf{r}_\perp^2}{\mathbf{r}_1^2 \left(\mathbf{r}_\perp - \mathbf{r}_1\right)^2} \times$$

$$\left[T(\mathbf{r}_1, Y) + T(\mathbf{r}_\perp - \mathbf{r}_1, Y) - T(\mathbf{r}_\perp, Y) - T(\mathbf{r}_1, Y) T(\mathbf{r}_\perp - \mathbf{r}_1, Y)\right]$$

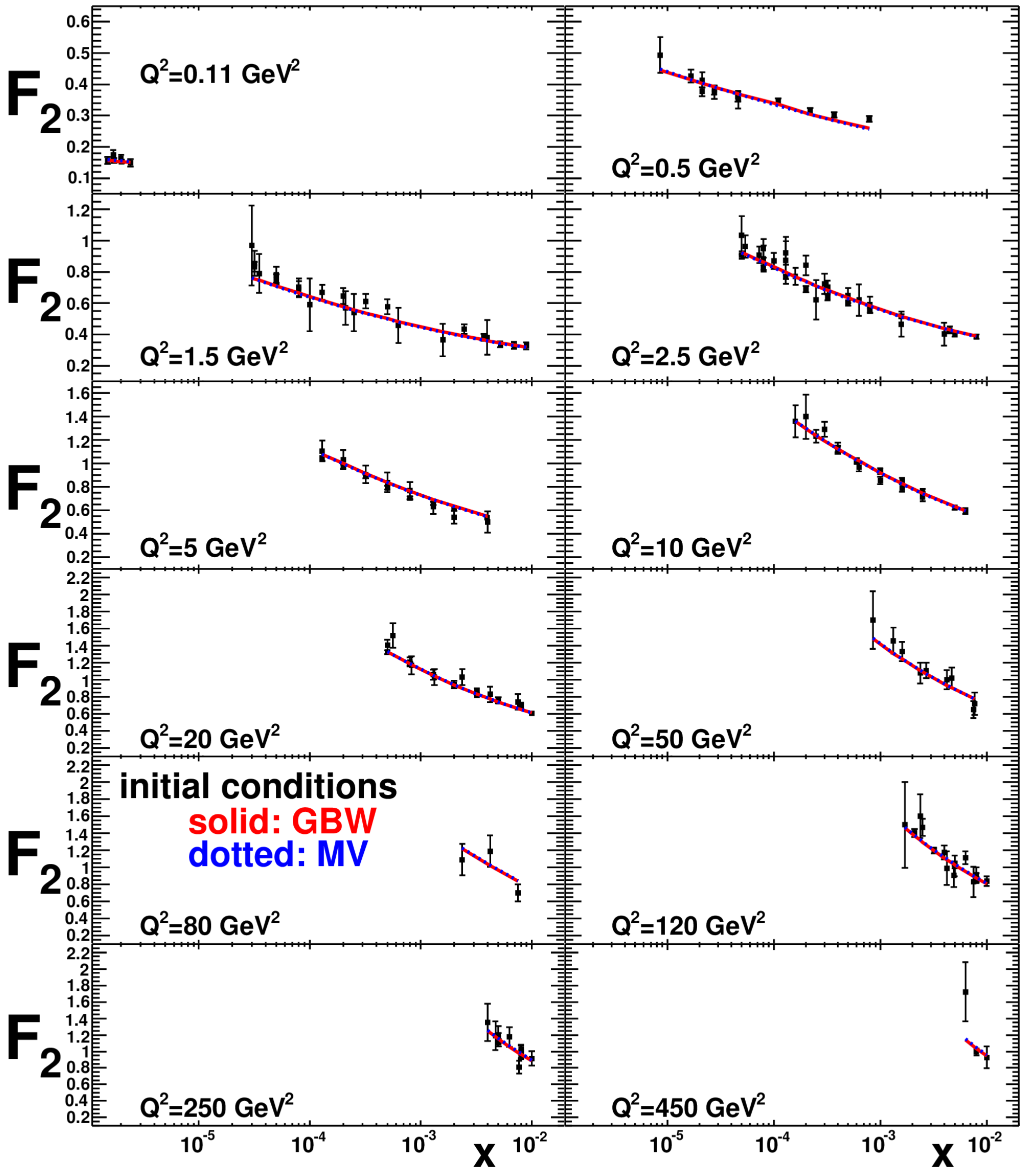
NLO BK Equation

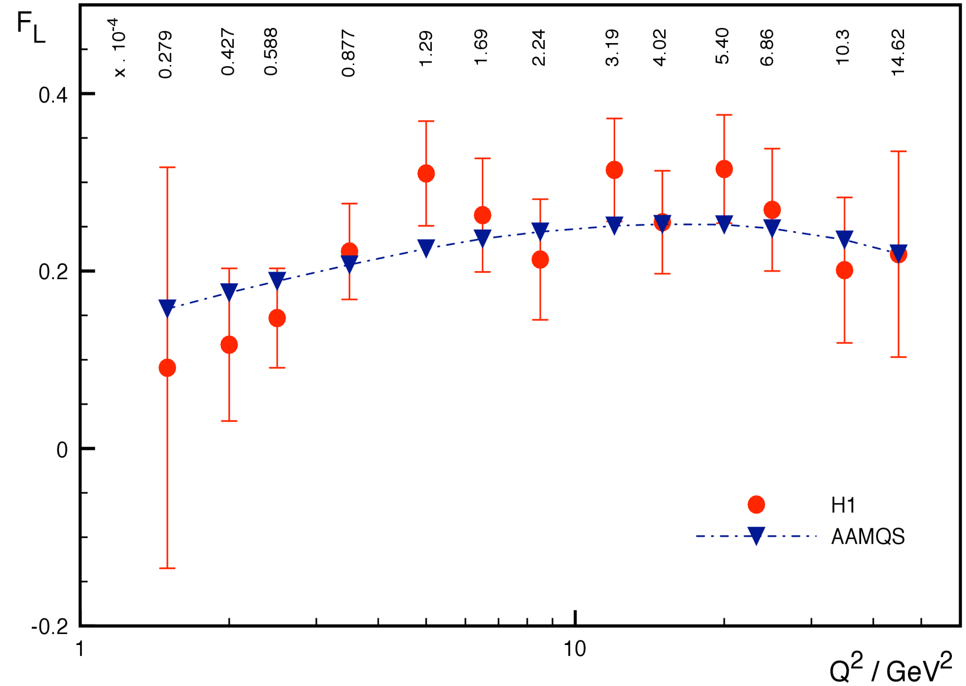
$$\frac{\partial T(\mathbf{r}_\perp, Y)}{\partial Y} = \int \mathrm{d}\mathbf{r}_1 \mathcal{K}_{\mathrm{Bal.}}(\mathbf{r}_\perp, \mathbf{r}_1, \mathbf{r}_\perp - \mathbf{r}_1) \times$$
$$[T(\mathbf{r}_1, Y) + T(\mathbf{r}_\perp - \mathbf{r}_1, Y) - T(\mathbf{r}_\perp, Y) - T(\mathbf{r}_1, Y) T(\mathbf{r}_\perp - \mathbf{r}_1, Y)]$$

$$\mathcal{K}_{\mathrm{Bal.}}(\mathbf{r}, \mathbf{r}_1, \mathbf{r}_2) = \frac{\alpha_s(\mathbf{r}) N_c}{\pi} \left[\frac{\mathbf{r}^2}{\mathbf{r}_1^2 \mathbf{r}_2^2} + \frac{1}{\mathbf{r}_1^2} \left(\frac{\alpha_s(\mathbf{r}_1^2)}{\alpha_s(\mathbf{r}_2^2)} - 1 \right) + \frac{1}{\mathbf{r}_2^2} \left(\frac{\alpha_s(\mathbf{r}_2^2)}{\alpha_s(\mathbf{r}_1^2)} - 1 \right) \right]$$

Balitsky, Chirilli PRD 77 014019
Kovchegov, Weigert NPA 784 188
Albacete, Kovchegov PRD 75 125021

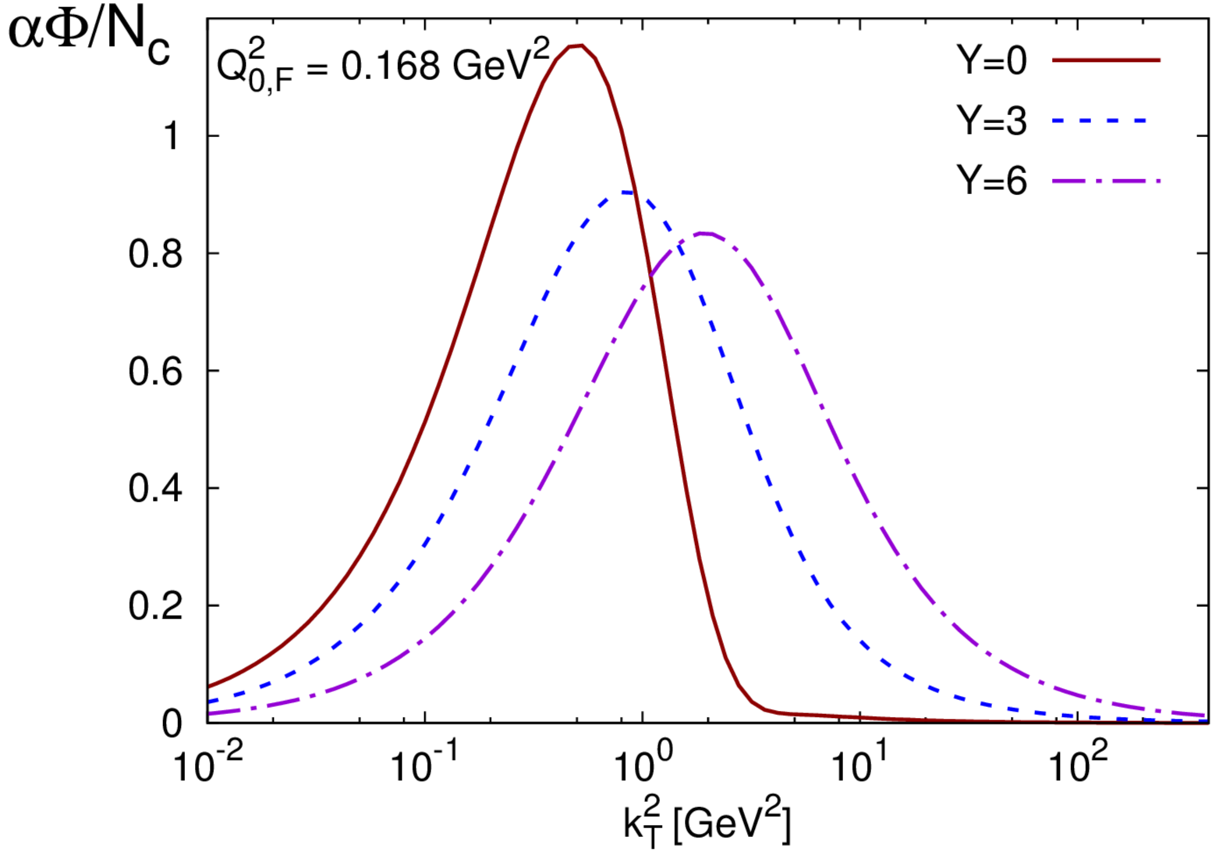
Deep inelastic scattering on the Proton





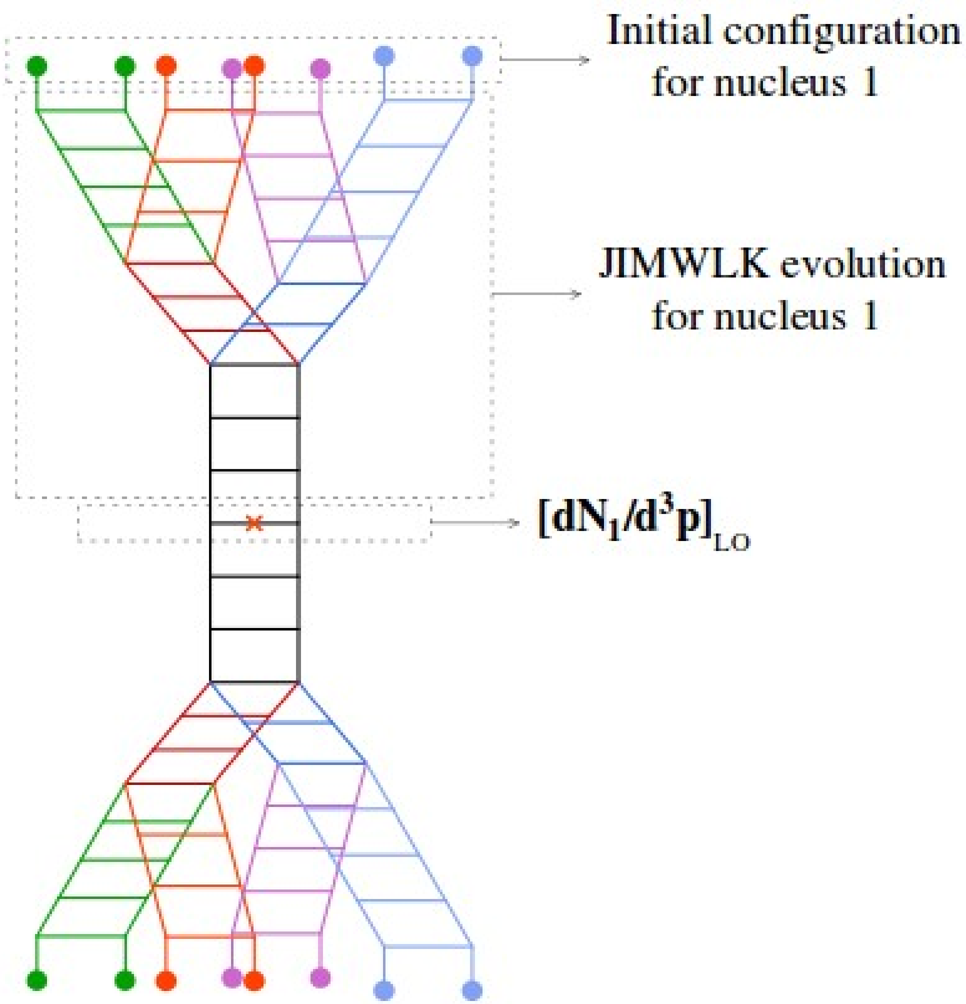
Albacete, Armesto, Milhano, Salgado; PRD80 (2009) 034031.
Quiroga-Arias, Albacete, Armesto, Milhano, Salgado; PRD80 J.Phys.G G38 (2011) 124124.

Unintegrated gluon distribution



$$\Phi_{A_{1,2}}(x,k_\perp) = \frac{N_c k_\perp^2}{4\,\alpha_s(\mathbf{k}_\perp)} \int \mathrm{d}^2\mathbf{r}_\perp \; J_0(k_\perp r_\perp)\; \left[1 - T_{A_{1,2}}(r_\perp, \ln(1/x))\right]^2$$

k_T factorization: single gluon production



$$\left\langle \frac{\mathrm{d}N_1}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y_p} \right\rangle_{\mathrm{LLog}} = \frac{8\alpha_s(p_\perp)S_\perp}{C_F(2\pi)^4} \frac{1}{\mathbf{p}_\perp^2} \int \frac{\mathrm{d}^2k_\perp}{(2\pi)^2} \Phi_{A_1}(y_p, k_\perp) \Phi_{A_2}(y_p, p_\perp - k_\perp)$$

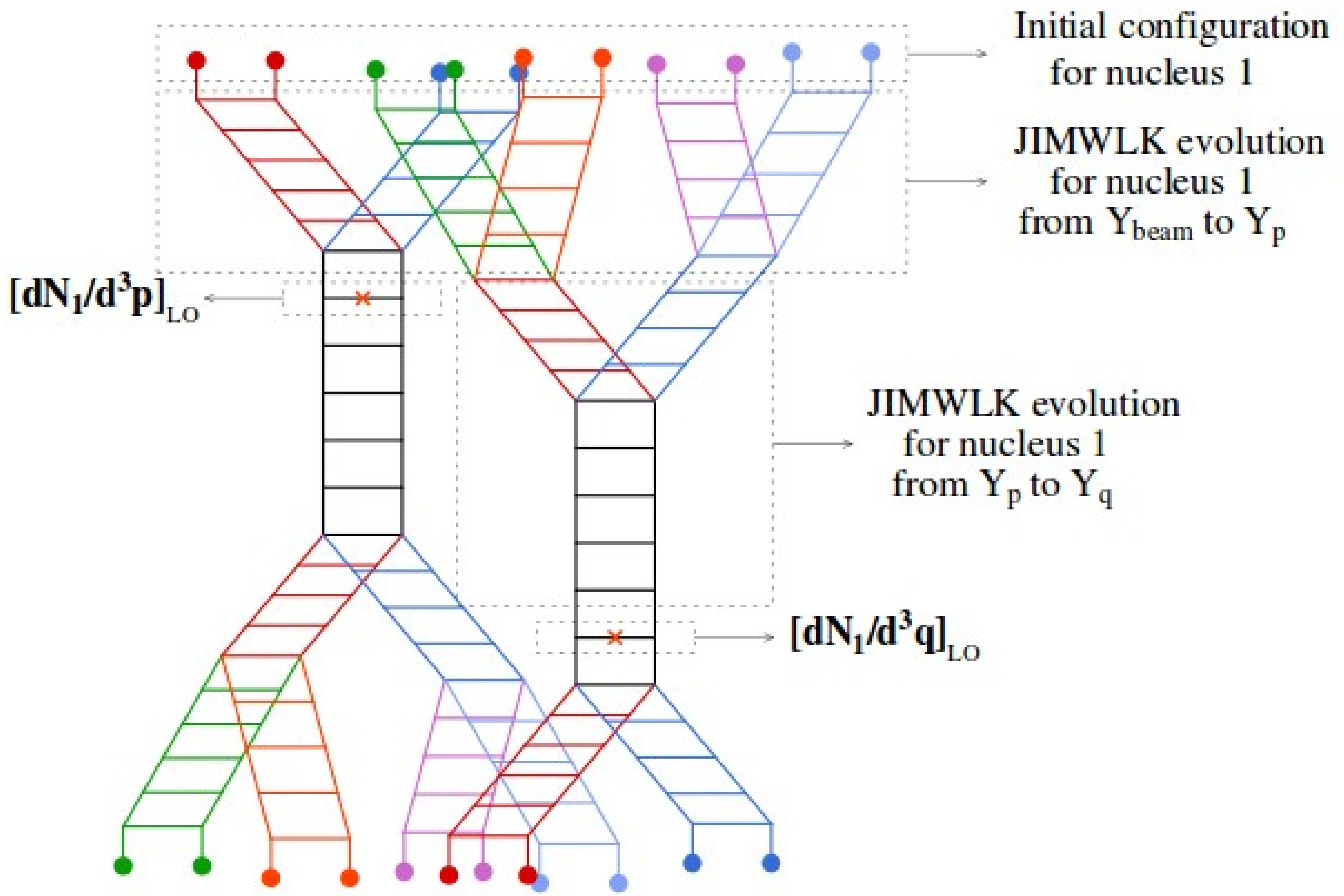
k_T factorization: double gluon production

$$\left\langle \frac{\mathrm{d}N_2}{\mathrm{d}^2\mathbf{p}_\perp \mathrm{d}y_p \mathrm{d}^2\mathbf{q}_\perp \mathrm{d}y_q} \right\rangle_{\text{LLog}} = \frac{32\alpha_s(\mathbf{p}_\perp)\alpha_s(\mathbf{q}_\perp)}{(2\pi)^{10} N_c C_F^3 \zeta} \frac{1}{\mathbf{p}_\perp^2 \mathbf{q}_\perp^2}$$

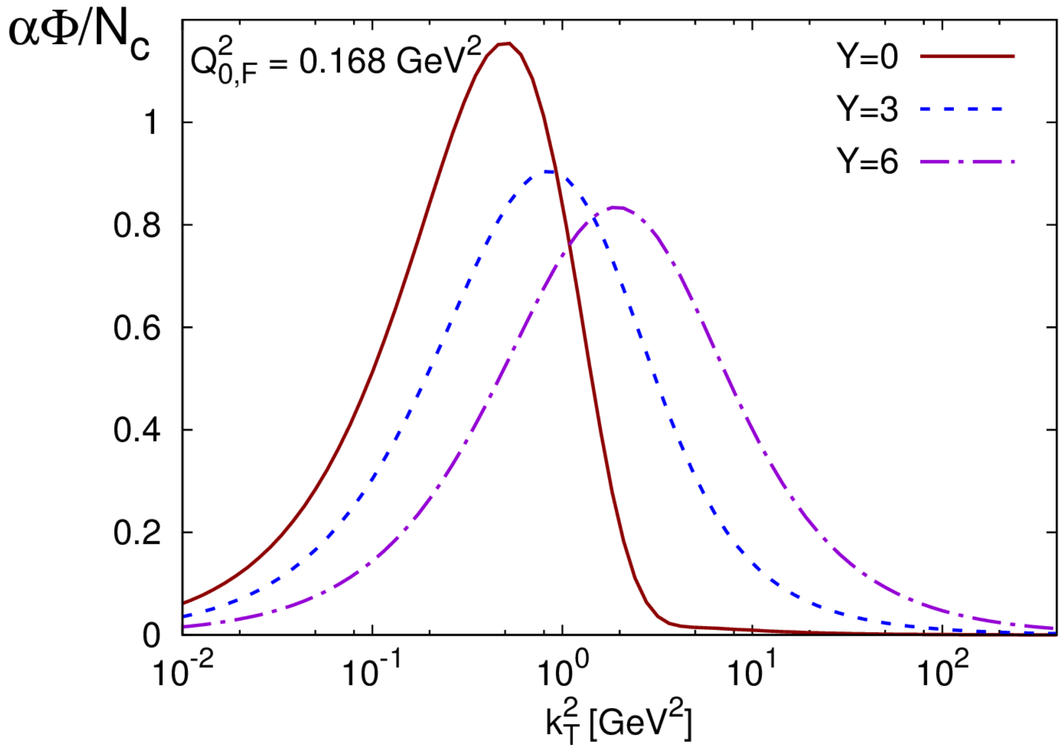
$$\begin{aligned}
\times \Bigg\{ & \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_1}^2(y_p, \mathbf{k}_{1\perp}) \Phi_{A_2}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_2}(y_q, \mathbf{q}_\perp + \mathbf{k}_{1\perp}) \\
+ & \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_1}^2(y_p, \mathbf{k}_{1\perp}) \Phi_{A_2}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_2}(y_q, \mathbf{q}_\perp - \mathbf{k}_{1\perp}) \\
+ & \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_2}^2(y_q, \mathbf{k}_{1\perp}) \Phi_{A_1}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_1}(y_q, \mathbf{q}_\perp + \mathbf{k}_{1\perp}) \\
+ & \int \mathrm{d}^2\mathbf{k}_{1\perp} \Phi_{A_2}^2(y_q, \mathbf{k}_{1\perp}) \Phi_{A_1}(y_p, \mathbf{p}_\perp - \mathbf{k}_{1\perp}) \Phi_{A_1}(y_q, \mathbf{q}_\perp - \mathbf{k}_{1\perp}) \Bigg\}
\end{aligned}$$

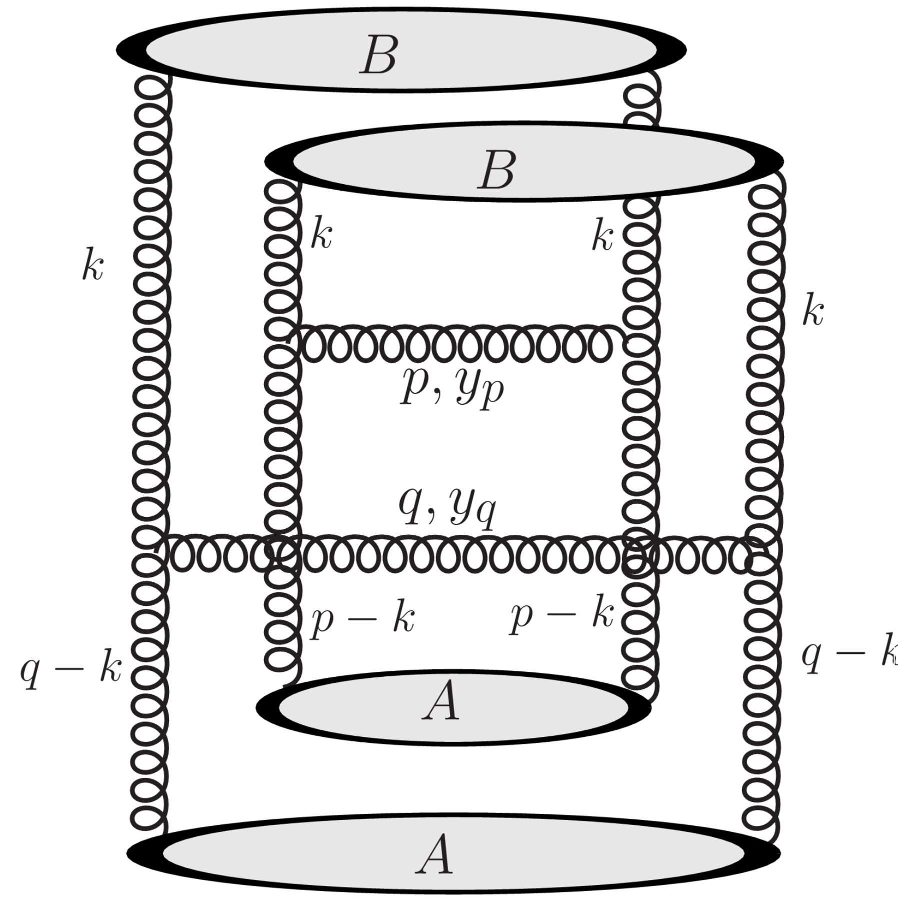
Gelis, Lappi, Venugopalan, PRD78, 050419 (2008).
PRD78, 054020 (2008).
PRD79, 094017 (2009).
Dusling, Gelis, Lappi, Venugopalan, NPA 836 159-182 (2010).

k_T factorization: double gluon production



Angular Structure



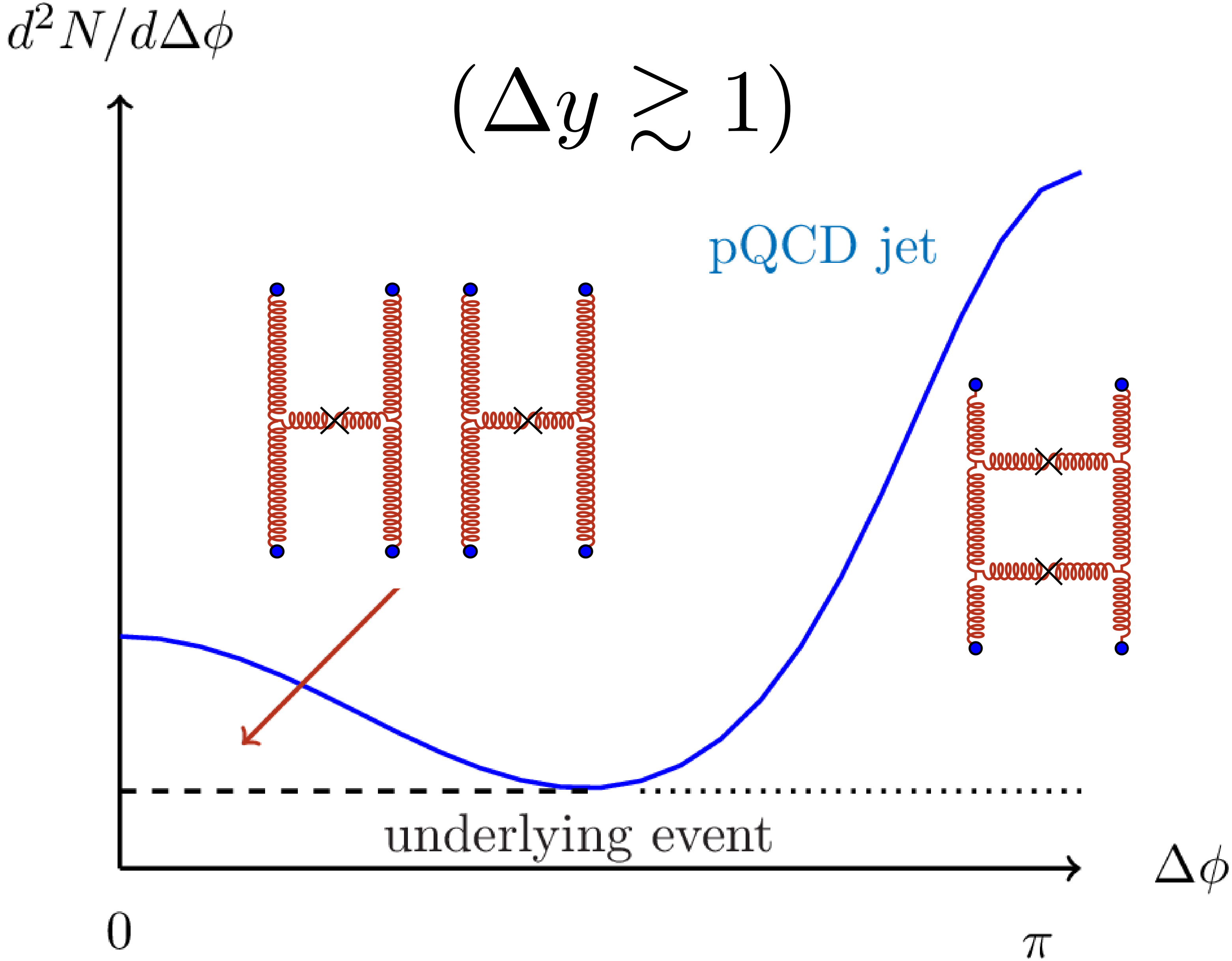


Condition for Ridge (Qualitatively):

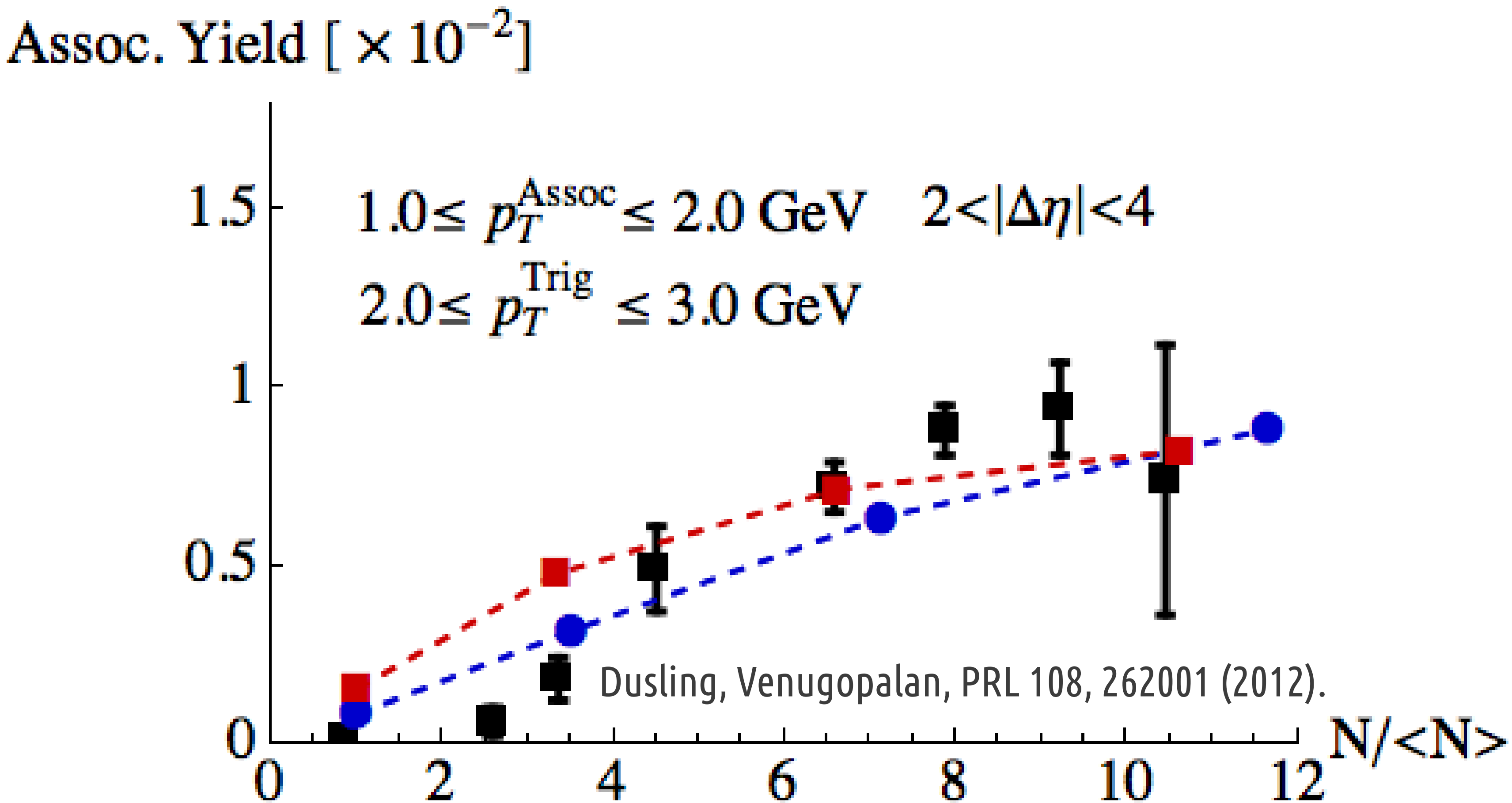
$$|\mathbf{k}_\perp| \sim |\mathbf{p}_\perp - \mathbf{k}_\perp| \sim |\mathbf{q}_\perp \pm \mathbf{k}_\perp| \sim Q_s$$

Dumitru, Dusling, Gelis, Lalilian-Marion, Lappi, Venugopalan, PLB 697 12-25 (2011).

Forward jet structure

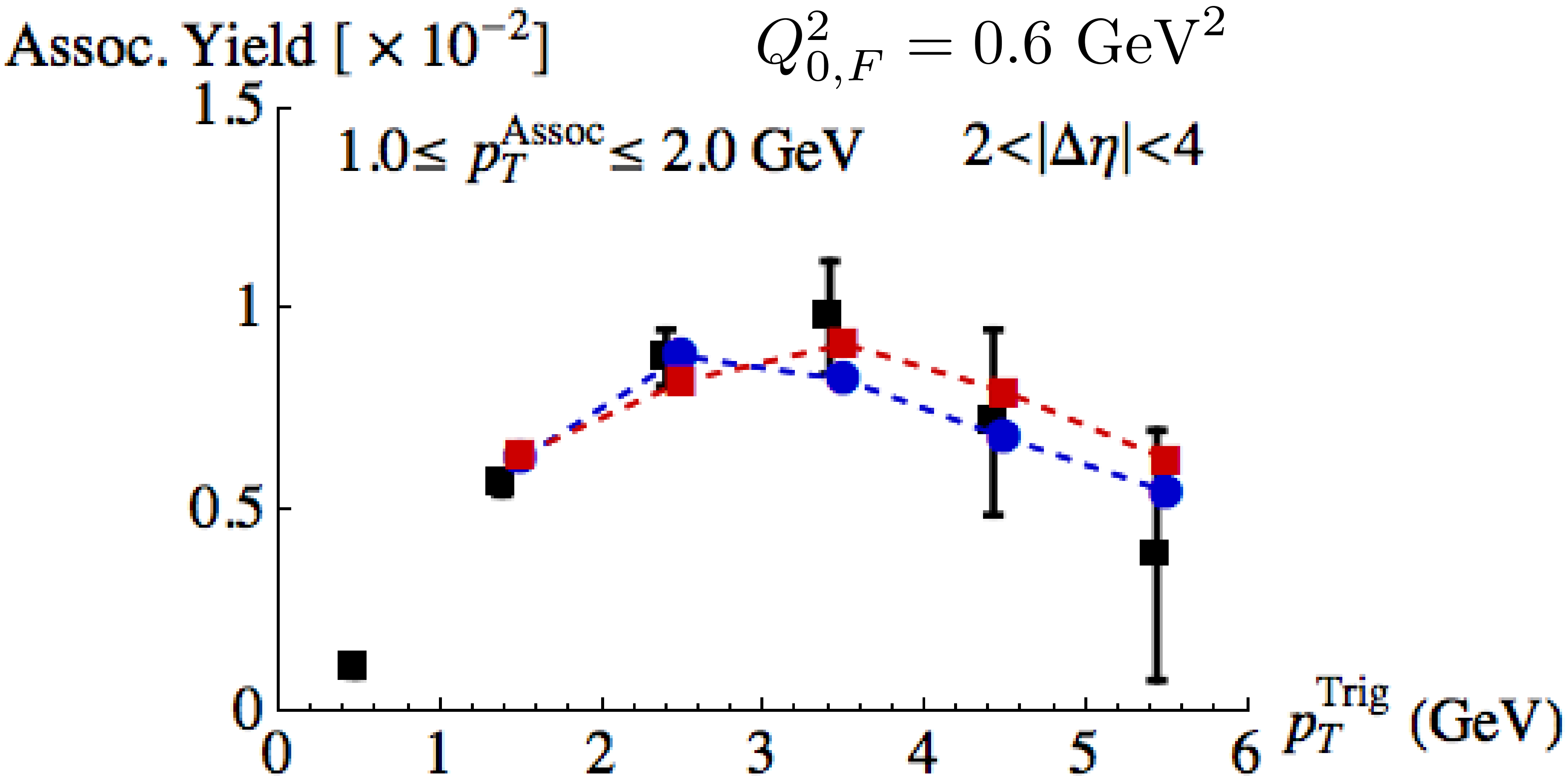


Centrality Dependence



$$Q^2_{0,F}(x_0 = 0.01) = 0.15, 0.3, 0.45, 0.6 \ \mathrm{GeV}^2$$

Trigger Dependence



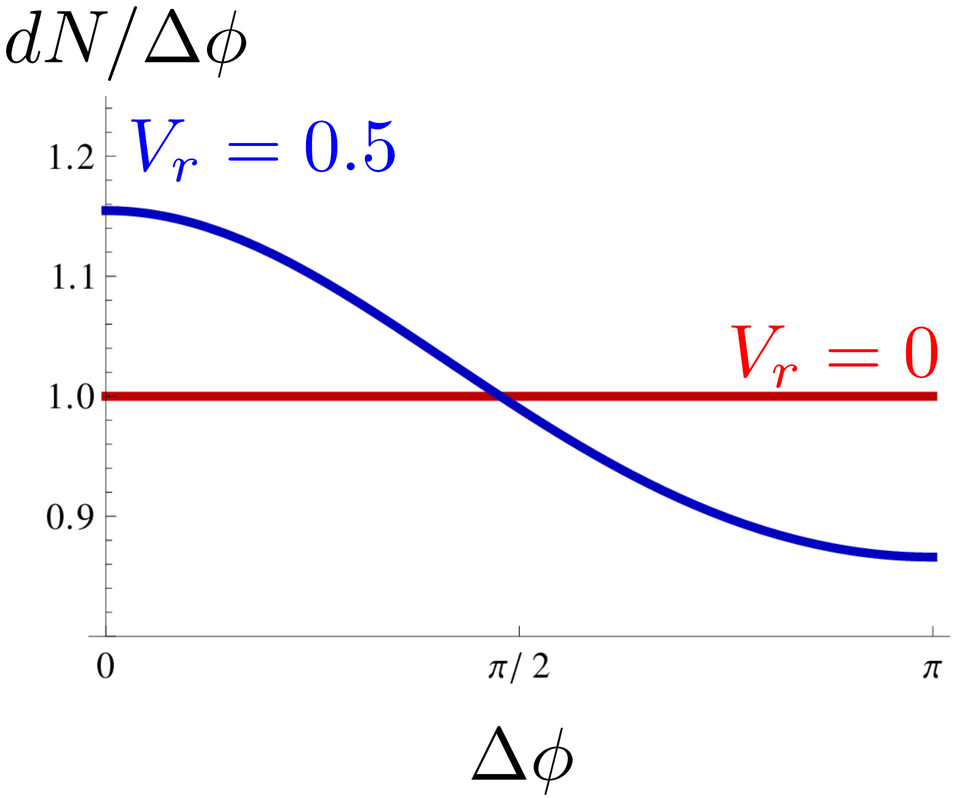
Blast Wave I

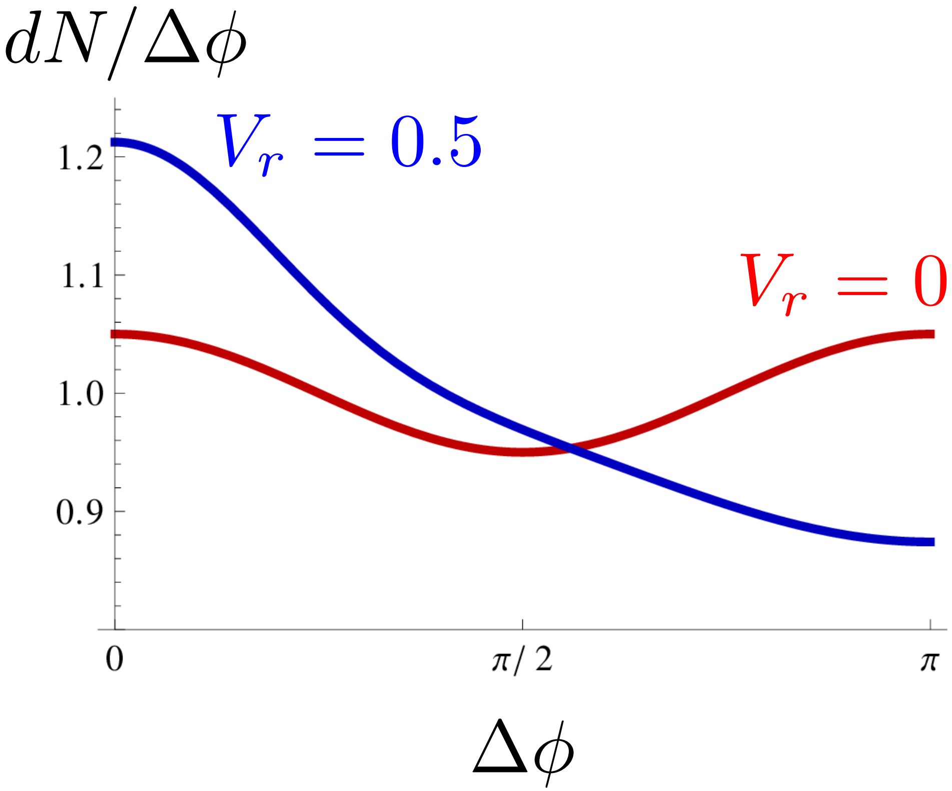
$$\frac{d^2N}{d\Delta\phi} = \int_{-\pi}^{\pi} d\Psi \mathcal{J}\left(\Psi, \Delta\phi\right) \frac{d^2N}{d\Delta\tilde{\phi}} \left(\Delta\tilde{\phi}\left(\Psi, \Delta\phi\right)\right)$$

$$2\sin^2\left(\frac{\Delta\tilde{\phi}}{2}\right) =$$
$$\frac{\sqrt{1-\beta^2}\left(1-\cos\left(\Delta\phi\right)\right)}{1-2\beta\cos\Psi\cos\left(\frac{\Delta\phi}{2}\right)+\frac{\beta^2}{2}\left(\cos\left(\Delta\phi\right)+\cos\left(2\Psi\right)\right)} \, .$$

$$\mathcal{J} = \frac{1-\beta^2}{\left(1-\beta\cos\left(\Psi+\Delta\phi/2\right)\right)\left(1-\beta\cos\left(\Psi-\Delta\phi/2\right)\right)} \, ,$$

Blast Wave II

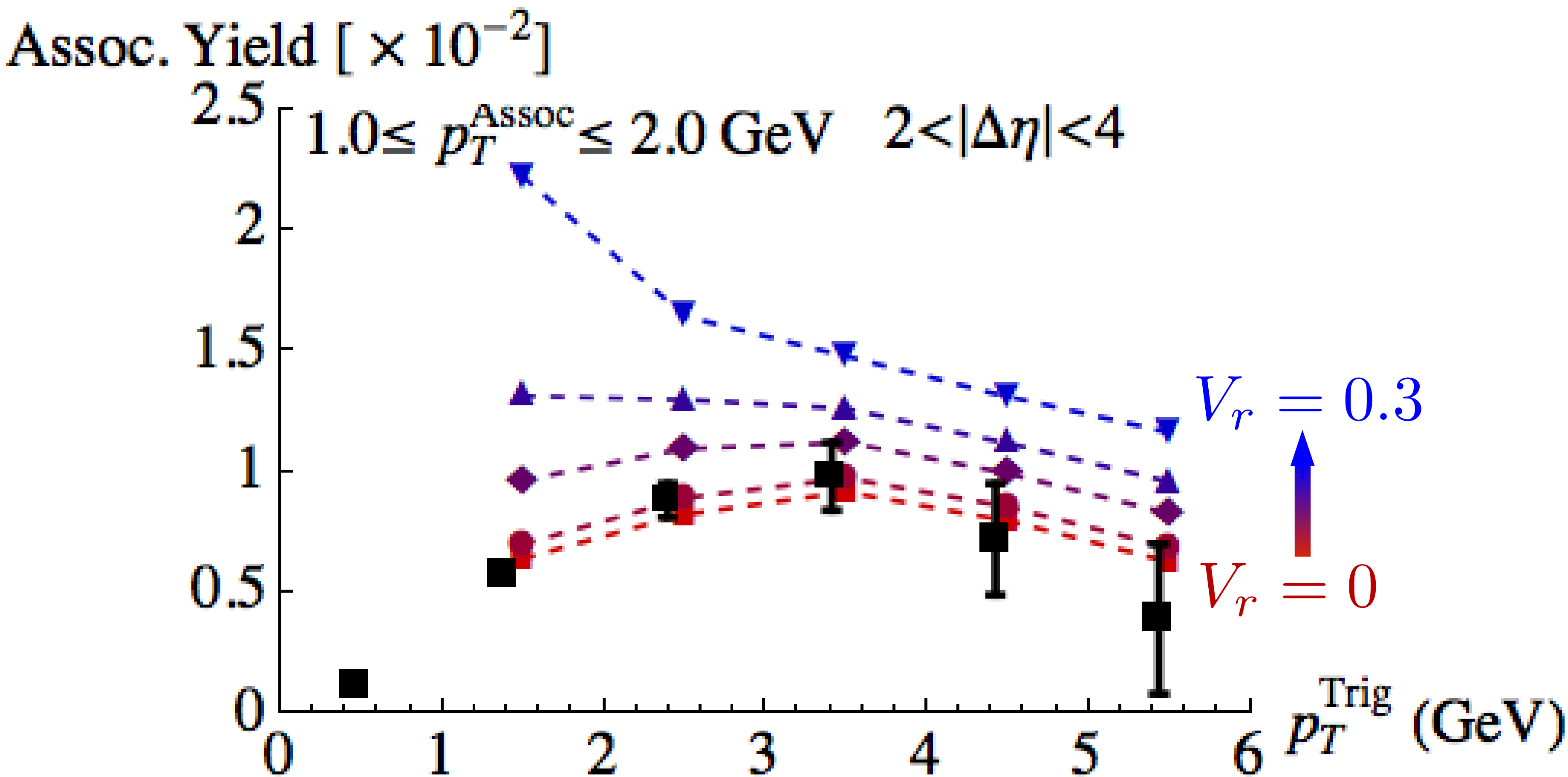




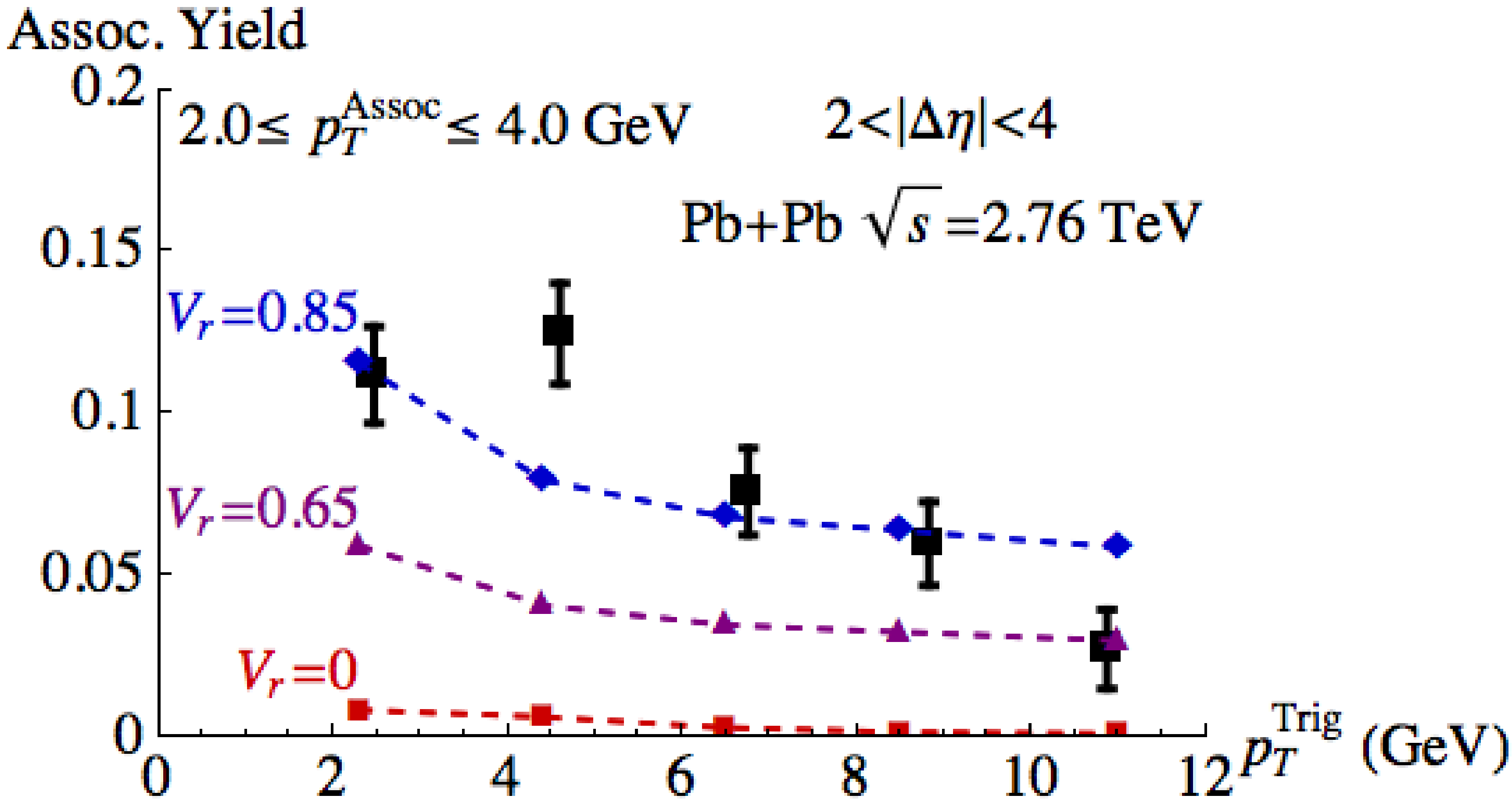
Left: No intrinsic correlation in $\Delta\phi$ followed by radial boost.

Right: Intrinsic azimuthal correlation followed by boost.

Blast wave results

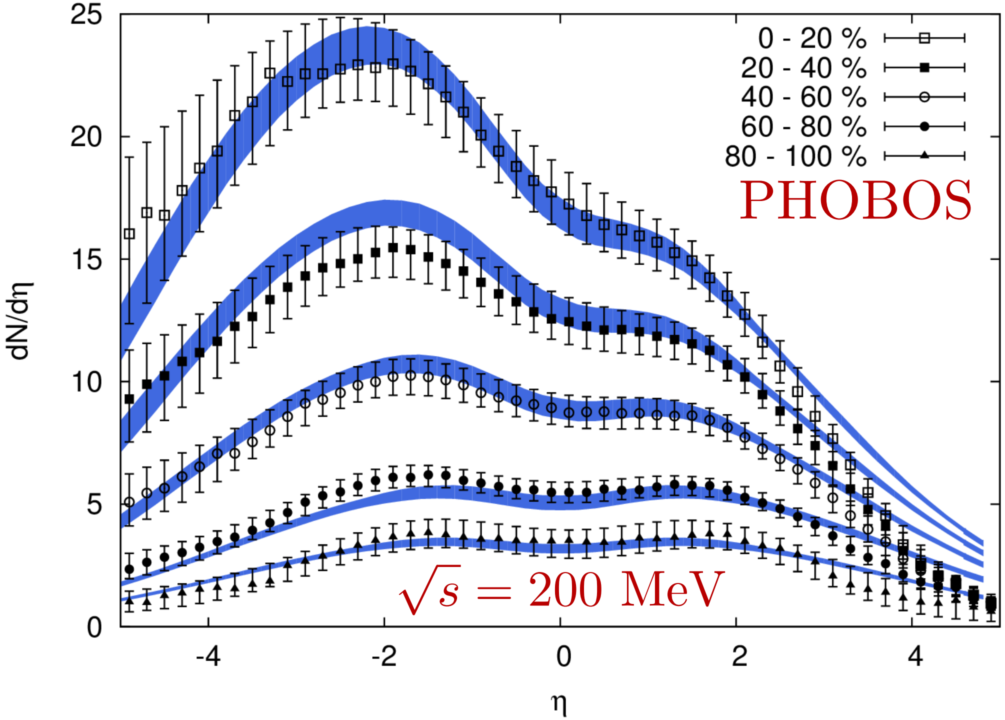


Results for Pb+Pb



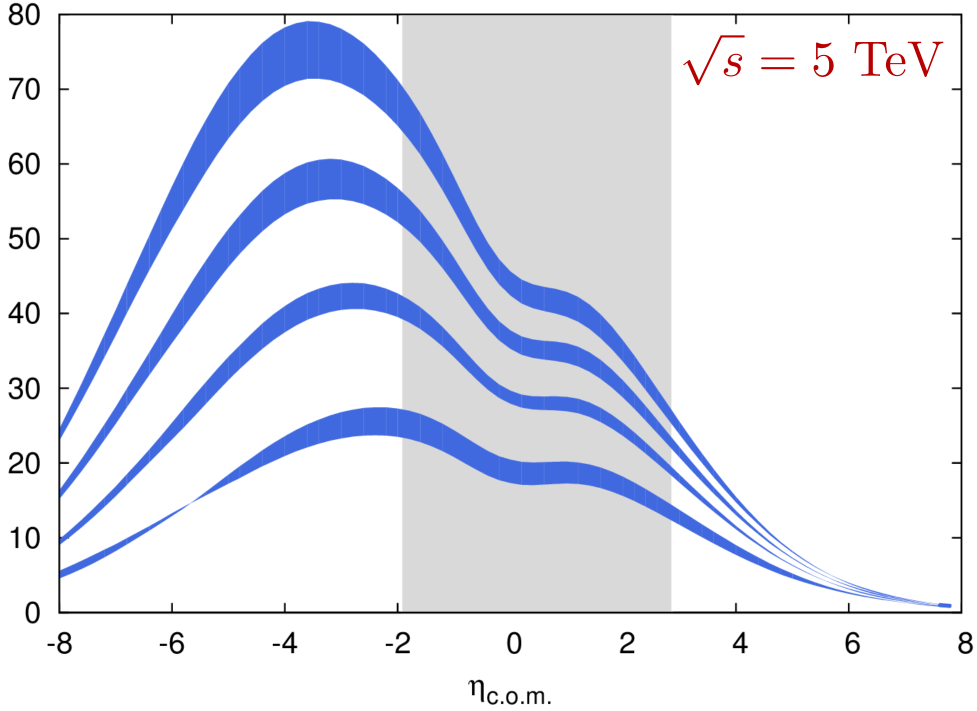
Multiplicity in p+Pb at 5 TeV

$Q^2_{0,\mathrm{Au}} = 0.336, 0.336, 0.504, 0.672, 0.840\ \mathrm{GeV}^2$



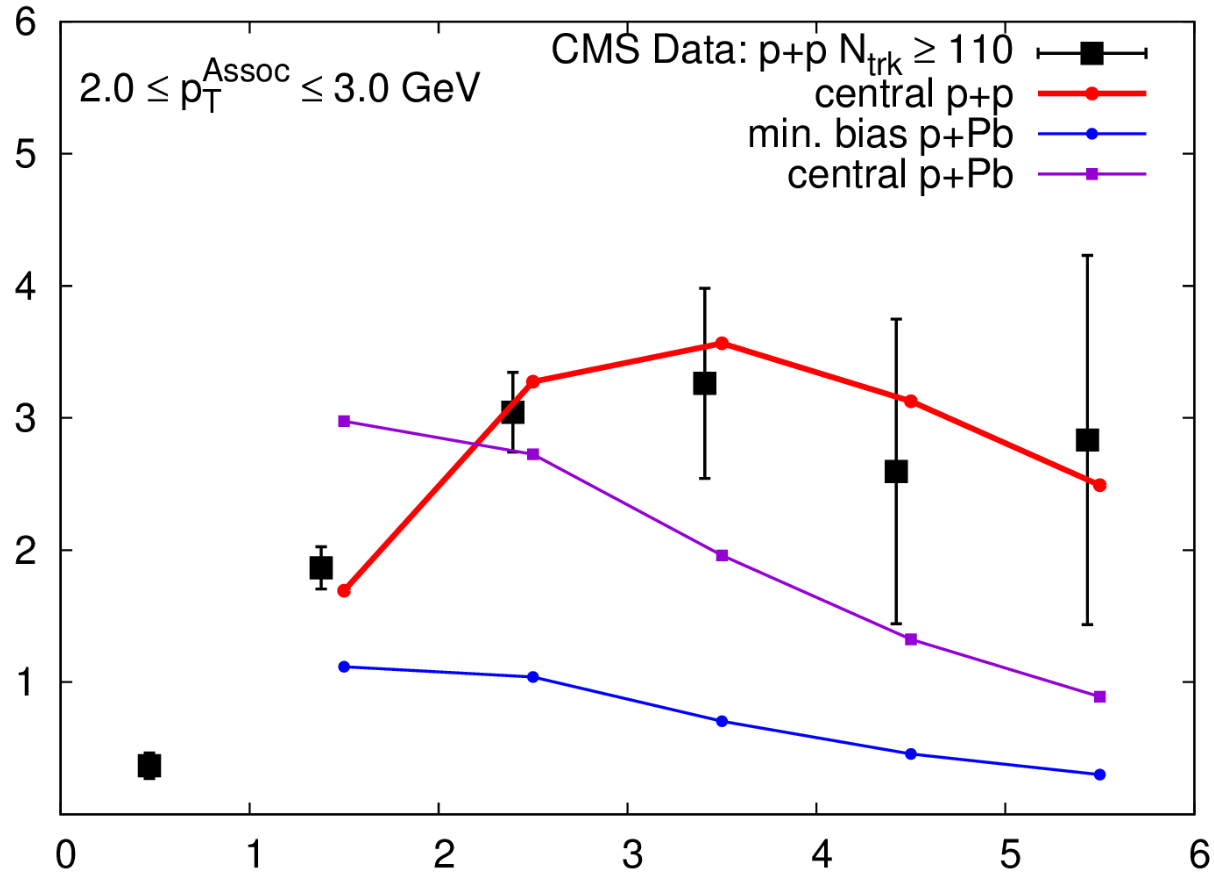
$Q^2_{0,\mathrm{d}} = 0.336\ \mathrm{GeV}^2$

$Q^2_{0,\mathrm{Pb}} = 0.504, 0.672, 0.840, 1.008\ \mathrm{GeV}^2$



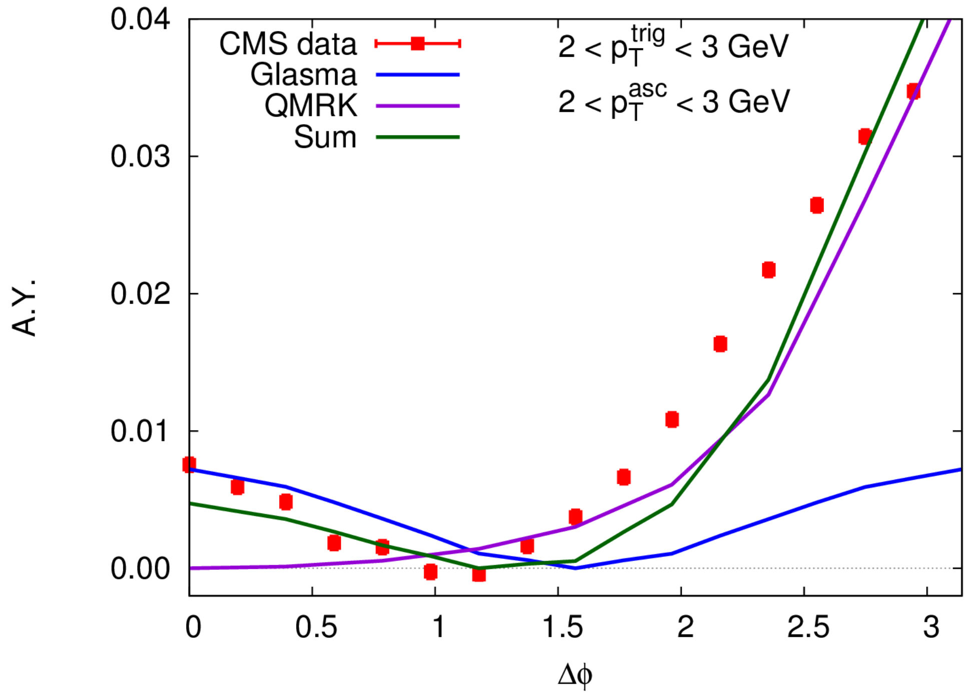
$Q^2_{0,\mathrm{p}} = 0.168\ \mathrm{GeV}^2$

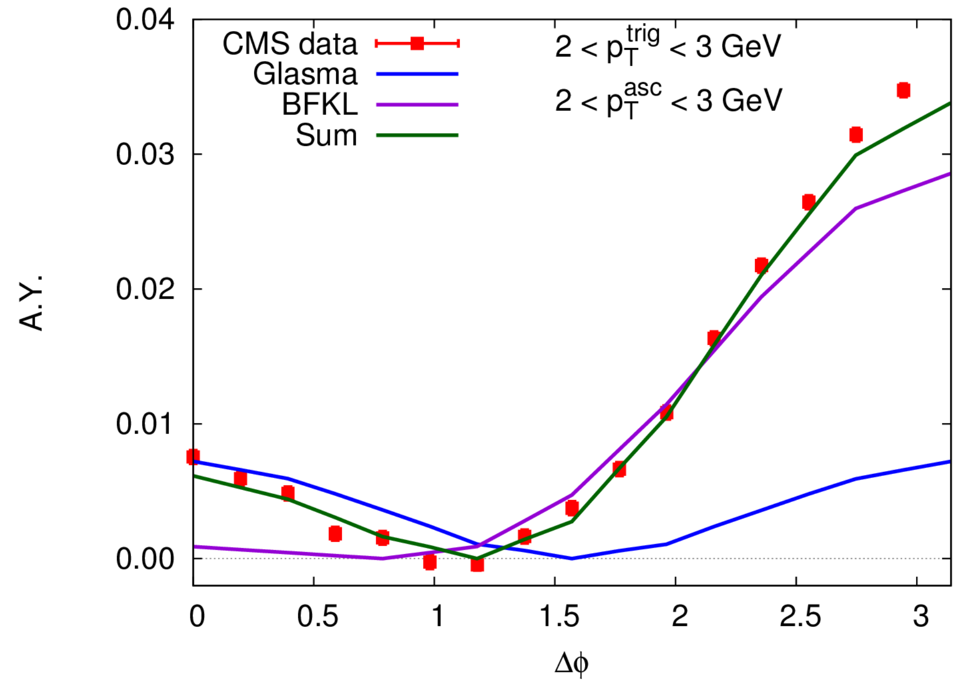
Ridge in p+Pb



Ridge in p+Pb is smaller than in p+p for CMS acceptance.
Signal will also have to be pulled from a larger background.

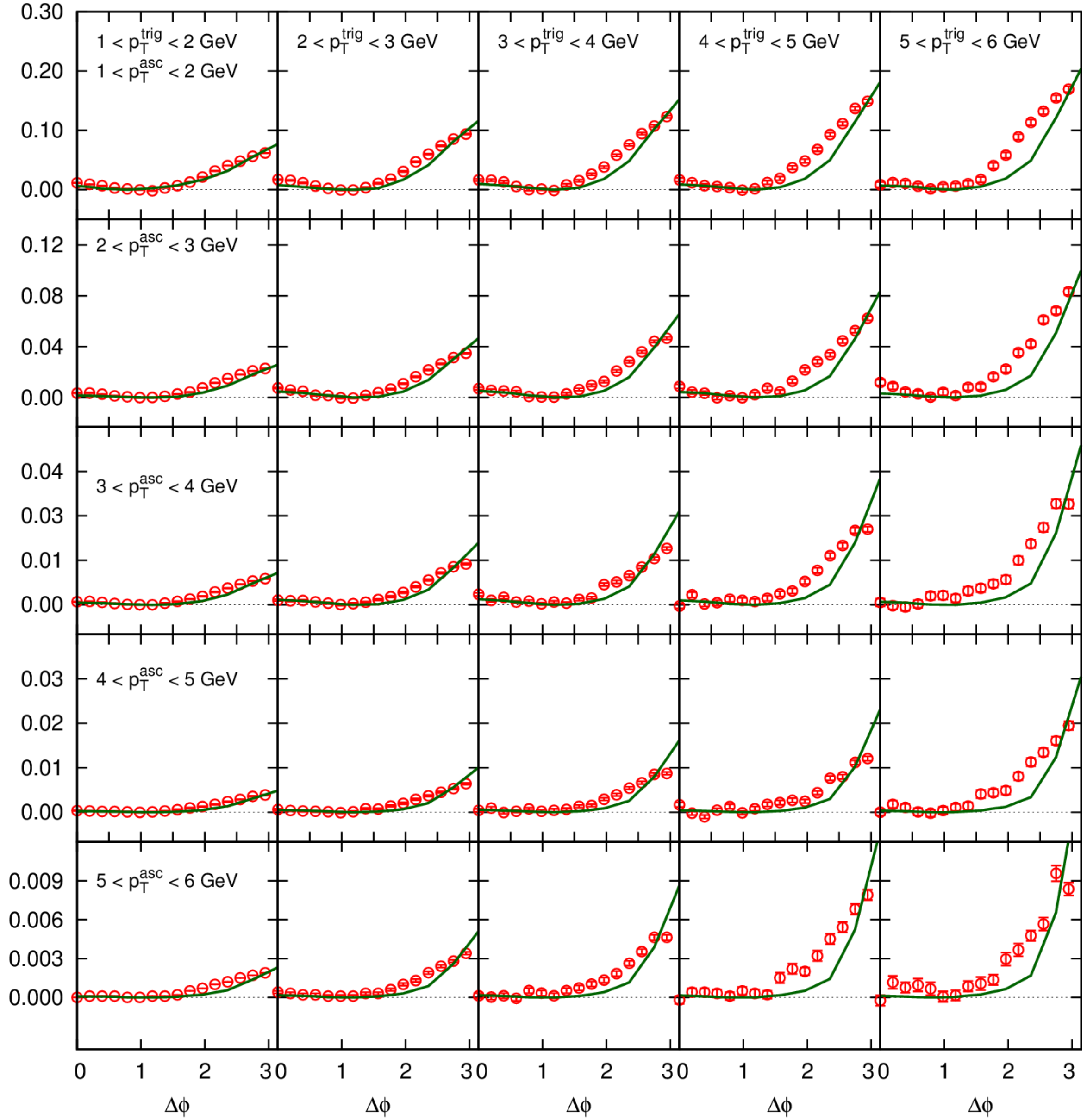
Understanding the away-side





There is a clear need for evolution between the triggered particles
(even for a rapidity gap as small as 2-4 units)

Jet Structure

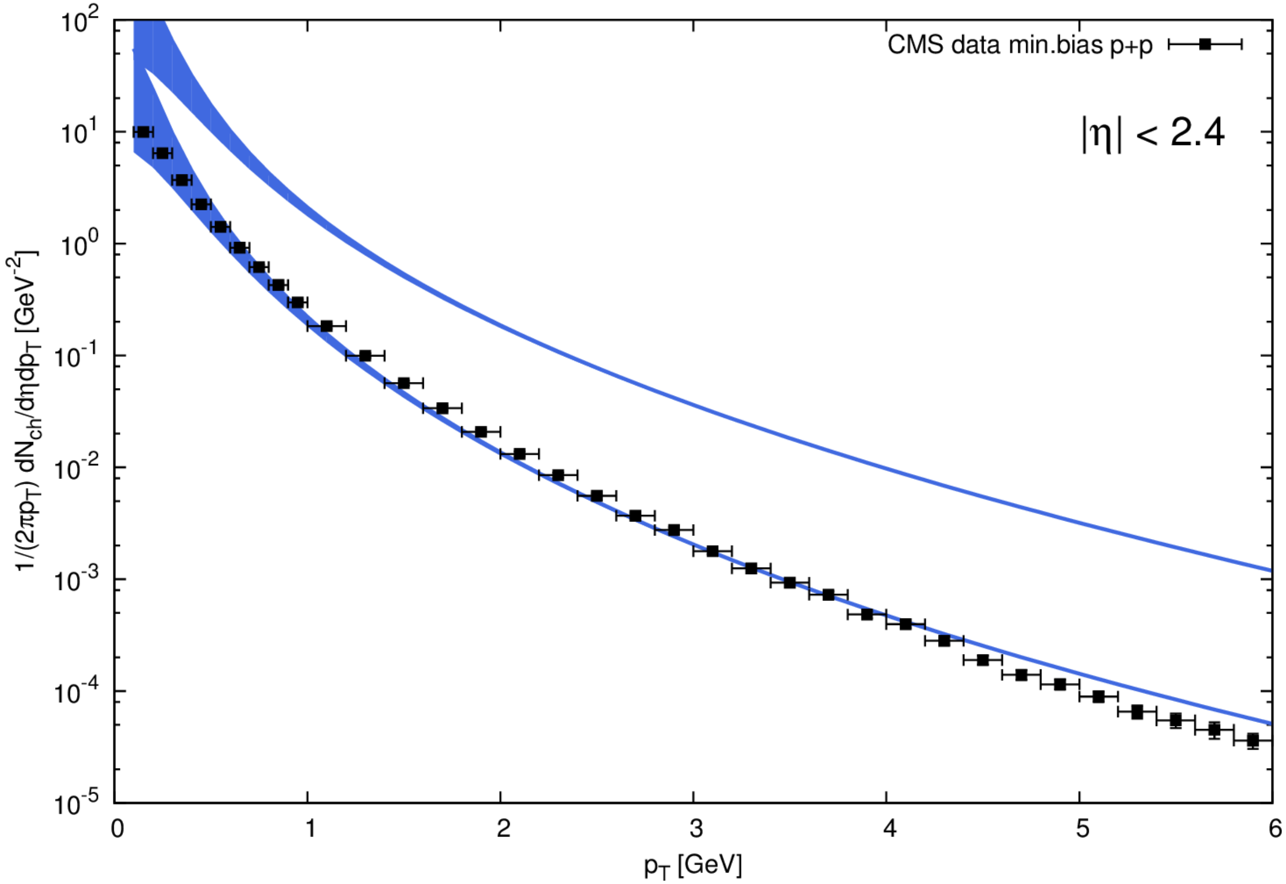


Summary

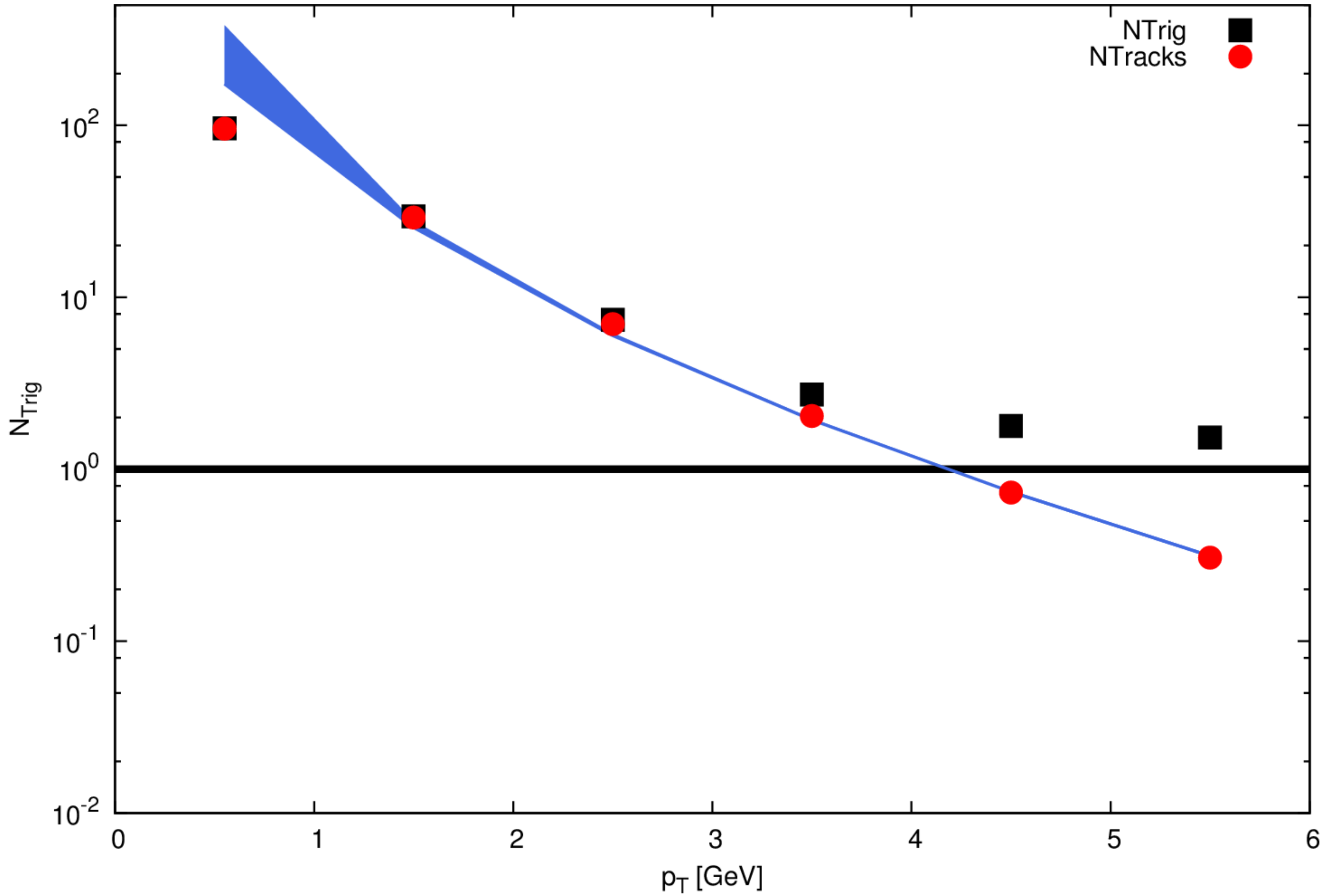
- Strong color sources lead to α_s^8 enhancement of QCD diagram responsible for near-side enhancement
- Structure of ridge correlation constrains radial flow in p+p
- Radial flow explains identical measurements in Pb+Pb
- Ridge tougher to see in asymmetric collisions

Backup

p+p p_T distribution



CMS Acceptance



BFKL Formalism

$$\frac{d^2 N_{AB}}{d^2\mathbf{p}_\perp d^2\mathbf{q}_\perp dy_p dy_q} = \frac{32 N_c \alpha_s(\mathbf{p}_\perp)\alpha_s(\mathbf{q}_\perp)}{(2\pi)^8 C_F}\frac{1}{\mathbf{p}_\perp^2\mathbf{q}_\perp^2}$$
$$\times \int d^2\mathbf{k}_{0\perp}\int d^2\mathbf{k}_{3\perp}\,\Phi_A(x_1,\mathbf{k}_{0\perp})\Phi_B(x_2,\mathbf{k}_{3\perp})\mathcal{G}(\mathbf{k}_{0\perp}-\mathbf{p}_\perp,\mathbf{k}_{3\perp}+\mathbf{q}_\perp,y_p-y_q)$$

$$\mathcal{G}(a,b,\Delta y) = \frac{1}{(2\pi)^2}\frac{1}{(a^2b^2)^{1/2}}\sum_n e^{in\overline{\phi}}\int_{-\infty}^{+\infty} d\nu\; e^{\omega(\nu,n)\Delta y} e^{i\nu\ln\left(a^2/b^2\right)}$$

$$\omega(\nu,n) = -2\overline{\alpha}_s \mathrm{Re}\left[\Psi\left(\frac{|n|+1}{2}+i\nu\right)-\Psi(1)\right]$$

$$\overline{\alpha}_s \equiv \frac{N_c\alpha_s\left(\sqrt{ab}\right)}{\pi}$$

$$\overline{\phi} \equiv \arccos\left(\frac{a\cdot b}{|a|\;|b|}\right)$$